THE USE OF HORIZONTAL WELLS FOR ENVIRONMENTAL REMEDIATION OF THE LF-1 PLUME AT THE MASSACHUSETTS MILITARY RESERVATION, CAPE COD, MASSACHUSETTS

by

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The Use of Horizontal Wells for Environmental Remediation of the LF-1 Plume at the Massachusetts Military Reservation, Cape Cod, Massachusetts

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ABSTRACT

The use of horizontal wells for remediation of the LF-1 (landfill) plume at the Massachusetts Military Reservation on Cape Cod was evaluated as part of a larger research project. This thesis contains an overview of the requirements of the LF-1 site and a discussion and comparison of the available horizontal well technology, and its performance and cost versus vertical wells.

The evaluation found that horizontal wells have several practical, performance, and economic advantages over vertical wells and can be used for several applications, including the following: soil vapor extraction; use in traditional pump and treat remediation systems; air sparging; injection of bioenhancers for bioremediation; NAPL investigation and recovery; vadose zone monitoring; and leachate collection; as well as hydraulic gradient control (i.e., pumping).

For bioremediation at the LF-1 site, horizontal wells can be used to create aerobic and anaerobic biozones for contaminant degradation and to inject nutrients with greater efficiency than vertical wells. Because horizontal wells can be oriented in any direction in the subsurface, they can be very effective for DNAPL investigation, and remediation of DNAPLs. And because horizontal wells can be installed beneath surface obstructions, they can be used for landfill post-closure activities such as monitoring or retroactive leachate control.

Many types of drilling systems are available and final selection requires input from experienced contractors. However, the most commonly used in the environmental industry are medium rigs which utilize rotary drilling with a mud motor; either a walkover radio-frequency guidance system for shallow bores or a downhole electromagnetic telemetry guidance system for deeper bores; and a drilling fluid which does not spread existing contamination, contribute new contamination, or damage the formation's permeability while having the proper balance of viscosity and gel strength to efficiently remove drill cuttings. In addition, the selection of well materials, such as well screen/liner, filter pack, and pumps are very important. The well screen must be durable, corrosion resistant, and somewhat flexible. Its length, diameter, and slot size will depend on the site conditions and the design goals of the application.

Thesis Supervisor: Charles C. Ladd
Title: Edmund K. Turner Professor of Civil and Environmental Engineering

Acknowledgments

This has been an interesting school year. Here are some of the highlights:

- I moved from San Francisco, California, to Boston, Massachusetts, and had to adapt to a foreign way of life. What's up with that white stuff on the ground in the wintertime, anyways?
- I met some of the coolest people on the face of this earth, many of whom I know I will be friends with for the rest of my life. (Hey, Patrish, Juancho, and Jer-bear.)
- And, of course, there's the thesis.

These are the people without whom this whole undertaking would 1) not have been possible, and/or 2) have been a lot less fun than it was. I hope I don't forget anybody. Here goes...

My mom in Monterey, my dad in Kansas City, my brother Larry in Santa Barbara, and my kid sister Dorian in Nashville gave me a lot of love, encouragement, and one of the highest phone bills at MIT.

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My partners in crime: Patricia Llana, my best friend at MIT and the coolest chick in Course 2, Héctor Cruzado, mi hermano puertorriqueño, and Jerry King, our cornfed Chinese boy. The rest of my non-M.Eng. friends who made it fun to be at MIT: Ulf Baumann, Mark Chow, Don Danmeier (my Fluid Mechanics TA at Cal), and Rosanna Tse, fellow Cal Bears; Sal di Bernardo, Carlos Gallegos, Casey Kim, Gilbert Mosqueda, Lisa Saldana, and Emma Shepherdson, my lunchtime posse from the Structures group; Connie Krause, my roommate ("if you are boiled in oil, you will be dead"); Ike Trefz, the Philly boy who lives on my floor and lets me "guest star" on his radio show (and who let me use the Course 6 scanner), and Ankur "Punk Rocker" Garg, my two favorite EECS geeks; Laura MacDonald and Kit Ogilvie, the two coolest chicks at BU; Tara Hunsucker, my old high school buddy; Ralph Olayé; and Jason Switzer, the coolest granola crunchin' Canadian boy I've ever met.

Last but not least, Glenn Curtis, my kick-ass 'Zona boy.

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1. INTRODUCTION

This thesis presents the results of a research project investigating the Main Base Landfill plume (LF-1) at the Massachusetts Military Reservation (MMR) in Cape Cod, Massachusetts. This project was conducted as a part of the course requirements for the Master of Engineering program in Civil and Environmental Engineering at the Massachusetts Institute of Technology.

1.1 Group Objectives

The group report (Haghseta et al., 1997) examines five aspects of the plume in order to meet the objective of plume containment and remediation:

1) A detailed site characterization documents the nature and extent of contamination.
2) A groundwater model simulates regional flow as well as a theoretical pumping scheme for plume containment.
3) A post-closure management plan aims for source containment for an extended time period.
4) A strategy for bioremediation offers a remedial alternative to the traditional pump and treat systems.
5) Horizontal well technology is examined for possible use in conjunction with bioremediation efforts.

The site characterization was conducted by examination of records and interviews with personnel associated with the site to ascertain the types of materials that were deposited into the landfill and when they were disposed. Further calculations were made to determine which chemicals may presently be in the plume due to that disposal.

The groundwater simulations were performed using the DYN system software, which combines hydrogeological data with appropriate rates of recharge to provide estimates of groundwater flow and define capture curves.

The post-closure management plan was developed using a cover system designed by an MIT student and completes the requirements set forth by the Commonwealth of Massachusetts for closure/post-closure management of a landfill.

The remediation scheme contains both the bioremediation and horizontal well technology aspects of the report. Research into the types of available and necessary nutrients, substrates, and microorganisms, as well as into the necessary injection rates of reactants and the possibility of using horizontal wells to perform that injection was also considered.

The group report details a possible containment and remediation scenario for LF-1. Through the examination of site characteristics, groundwater flow and capture curve analysis, post-closure management, bioremediation, and horizontal well technology, the following conclusions were made:

- Threats to drinking water supply and the local environment are posed by the exceedance of maximum contaminant levels by the chemicals of concern: TCE, PCE, and CCl_4.

- A pump and treat system can theoretically be used but is not practically feasible.
- Post-closure management is an effective tool for source containment.
- An effective bioremediation scheme can be implemented with proper consideration of the degradation capabilities of each contaminant of concern, and appropriate utilization of nutrients, substrates, and electron acceptors.
- Horizontal well technology can be used to inject deficient nutrients to aid in bioremediation.

1.2 Thesis Objective and Structure

The use of horizontal wells for remediation of the LF-1 plume at the Massachusetts Military Reservation on Cape Cod was evaluated as part of the larger research project. In addition to evaluating the use of horizontal wells for remediation of the LF-1 plume, this thesis is intended to give an overview of the requirements of the LF-1 site and a discussion and comparison of the horizontal well technology available, its performance, and its costs. The thesis is structured as follows.

1) Chapter 1 is a brief introduction placing this thesis in the context of the larger group report. It also contains a statement of the thesis objectives and outlines the thesis structure.

2) Chapter 2 gives background on the LF-1 site, including a description of the site and vicinity, a short description of the historical and current uses of the site, and a plume characterization.

3) Chapter 3 deals with the use of horizontal wells. It is divided into three main parts.

   - The description section details the advantages of horizontal wells over vertical wells; applications for which horizontal wells can be used, including bioremediation, DNAPL investigation and remediation, and post-closure management activities; and drilling systems, including guidance/navigational systems, solids control systems, drill rig power and capabilities, drilling methods, and a brief summary.

   - Next, the drilling plan section covers site-specific criteria for installation, including surface site conditions, subsurface stratigraphy, and hydrogeology of the site; and a discussion of the selection of well materials and placement of the wells.

   - Finally, the performance and economics of horizontal wells are compared with those of vertical wells.

4) Chapter 4 presents a summary and conclusions.

5) Chapter 5 contains a list of the references used for this thesis.

2. SITE BACKGROUND

2.1 Description

The MMR (Figure 2-1), which occupies approximately 22,000 acres within the towns of Bourne, Mashpee, and Sandwich on Cape Cod, has been used by the military since 1911. The MMR is operated by the Air National Guard, the Massachusetts Army National Guard, the US Air Force, the US Coast Guard, and the Veterans Administration. It is organized into four main areas: the Range Maneuver and Impact Area, the Cantonment Area, the Massachusetts National Cemetery, and the Cape Cod Air Force Station. Current operations at the MMR include Massachusetts Army National Guard and US Army Reserve training, US Coast Guard Air Station Cape Cod, US Air Force's Precision Acquisition Vehicle Entry - Phased Array Warning System missile and space vehicle tracking system, and the Veterans Administration's Massachusetts National Cemetery.

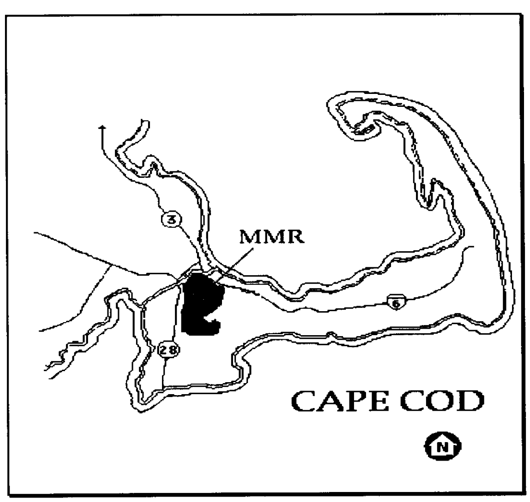


Figure 2-1, Location of MMR (Stone & Webster, 1996)

The Main Base Landfill (Figure 2-2) occupies approximately 100 acres in the southern part of the Range Maneuver and Impact Area, and is bounded by Herbert Road to the north, Turpentine Road to the east, Connery Road to the south, and Frank Perkins Road to the west. The terrain ranges from open to heavily wooded.

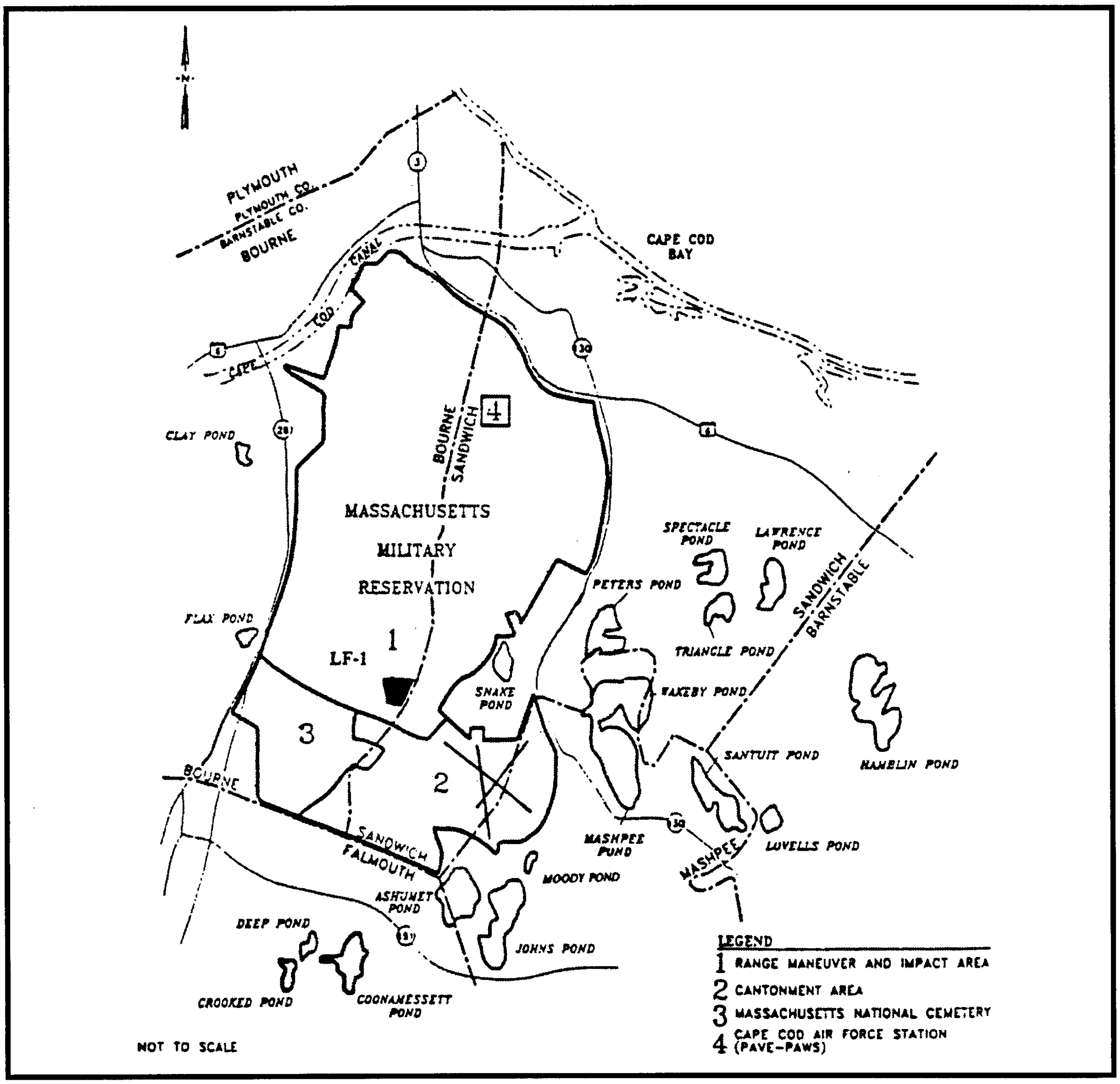


Figure 2-2, Main Base Landfill at MMR (CDM, 1996)

The Chemical Spill 9 (CS-9) Study Area is located immediately southeast and slightly upgradient of the landfill and is encompassed by the perimeter fence. Previous investigations in this area, a former motor pool, indicate that sources of soil contamination and potential sources of groundwater contamination from former underground storage tanks and abandoned leaching wells and sumps used for vehicle maintenance waste disposal exist at CS-9. CS-9 is currently the site of a bicycle-motorcross track.

Recreational land uses near the MMR include golfing; swimming, boating, and other water sports; fishing, boating, and water skiing on John's Pond and Ashumet Pond; and hunting and model plane flying in Shawme Crowell State Forest and Crane Wildlife Management Area. In addition, Camp Good New, a summer camp for young people, is located on Snake Pond.

The residences nearest to LF-1 are US Coast Guard base housing approximately 4,800 feet southwest, and private residences approximately two miles east in the town of Sandwich and approximately two miles west in the town of Bourne. The base housing area includes a chapel, a golf course, a base commissary, a medical dispensary, three public schools operated by the town of Bourne, and one private school.

2.2 Historical and Current Use

The Main Base Landfill has been the primary solid waste disposal facility at MMR since 1944. Waste disposal was unregulated until 1984. The disposal areas consist of five cells (designated by the last year of waste disposal in that cell) and a natural kettle hole. The six areas are the 1947, 1951, and 1957 cells, collectively called the Northwest Operable Unit (NOU); the 1970 and Post-1970 cells; and the Kettle Hole (Figure 2-3). Wastes believed to have been deposited in the cells include general refuse, fuel storage tank sludge, herbicides, solvents, transformer oils, fire extinguisher fluids, blank small arms ammunition, paints, paint thinners, batteries, dichlorodiphenyltrichloroethane (DDT) powder, hospital waste, municipal sewage sludge, coal fly ash, and possibly live ordnance.

Previous investigation showed that wastes were deposited in unlined linear trenches approximately 20 to 25 feet wide and several hundred feet long, and covered with approximately two feet of soil. The depth of the waste is estimated to be 20 to 30 feet below ground surface (bgs). Disposal ended in the last (Post-1970) cell in June 1989. Wastes are currently sent to an on-base transfer station and from there to the SEMASS incinerator in Rochester, Massachusetts.

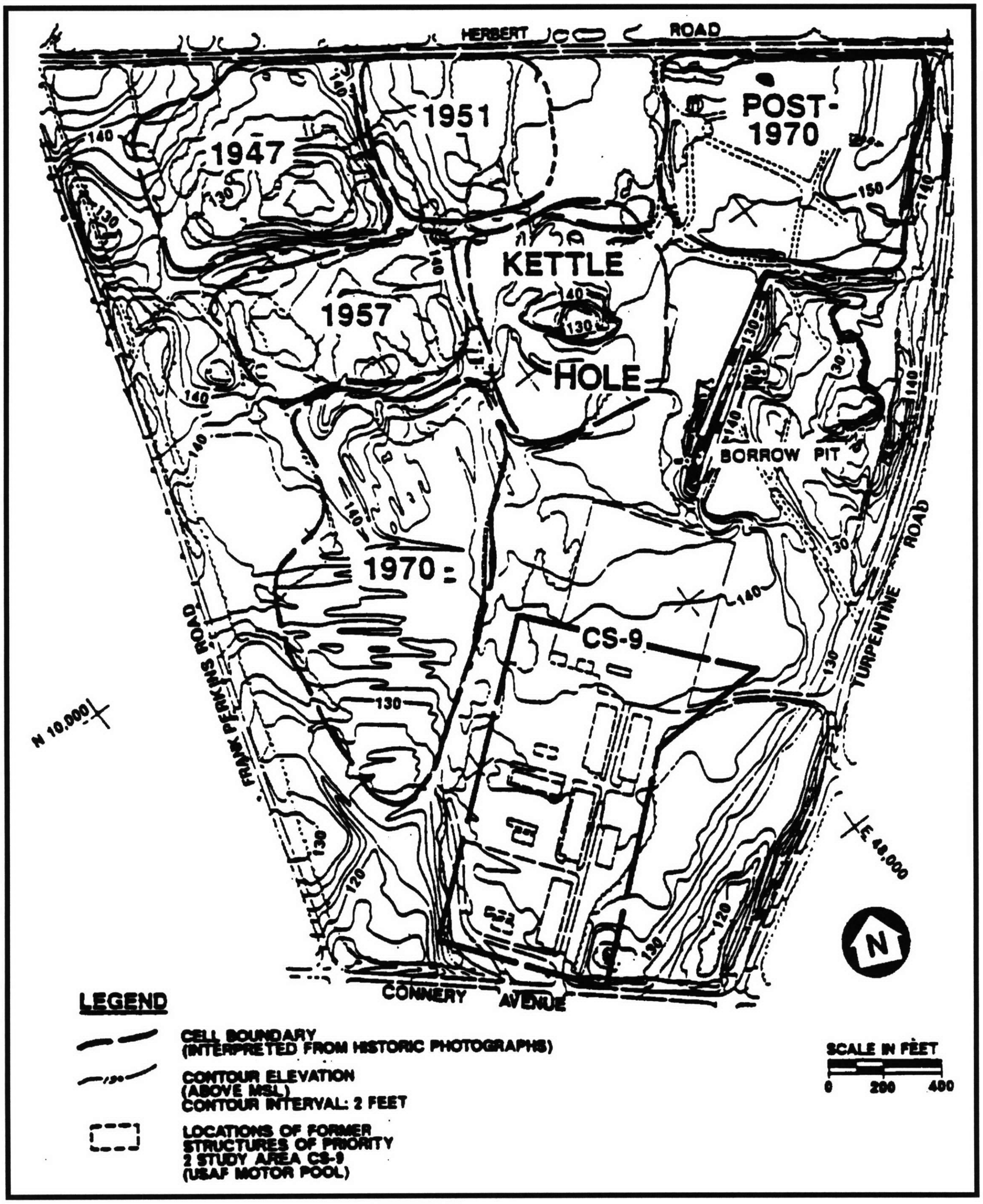


Figure 2-3, Main Base Landfill Cells (CDM, 1996)

A site investigation conducted by E.C. Jordan Co. in 1988 and remedial investigations conducted by ABB Environmental Services in 1989 and CDM Federal Programs Corporation in 1992-94 indicated that volatile organic compounds (VOCs), as well as semi-VOCs (SVOCs), pesticides, and inorganics, are present in groundwater beneath the site. It was determined that the resulting plume of chlorinated VOCs, primarily tetrachloroethylene (PCE), trichloroethylene (TCE), dichloroethylene (DCE), and carbon tetrachloride (CCl_4), originated from the 1970 cell, the Post-1970 cell, and the Kettle Hole areas. The main axis of the plume is migrating west towards Buzzards Bay at a rate of approximately 0.6 ft/day (Wagle, 1997), posing potential threats to the local environment.

Much of the information sources used in the preparation of this thesis are the reports which have been generated for the MMR Installation Restoration Program (IRP) office.

2.3 Plume Characterization

The LF-1 plume was previously thought to be composed of one main lobe with a smaller southern lobe, both traveling roughly westward. The latest information (February 1997) on the plume shows that it is actually composed of two distinct lobes of comparable dimensions (Figure 2-4). The plume as a whole extends approximately 17,000 feet westward from the Main Base Landfill and is approximately 5,000 feet at its widest point. The thickness of the plume varies from approximately 40 feet under the source areas at the landfill to more than 120 feet at its maximum. The plume is generally migrating west from the landfill towards Buzzards Bay at a rate of approximately 0.6 feet/day, with the northern lobe presently at Squeteague Harbor and the southern lobe just west of Route 28.

Although several chemicals are present in the plume, the two main contaminants of concern at LF-1 are PCE and TCE. The maximum detected concentrations for these compounds are 65 μg/L and 64 μg/L, respectively, which exceed the Maximum Concentration Limits for these compounds (5 μg/L). The PCE plume contains three areas of highest concentration with average values of 30 μg/L, 48 μg/L and 65 μg/L located at monitoring wells GB22, MW35, and MW103, respectively. The TCE plume also has three areas of highest concentration. The average concentrations are 19 μg/L, 26 μg/L, and 64 μg/L and are located at monitoring wells MW37A, MW38, and MW31, respectively. These wells are shown on Figure 2-5. The dissolved oxygen concentration at LF-1 ranges from not detected to approximately 10 mg/L (Haghseta, 1997).

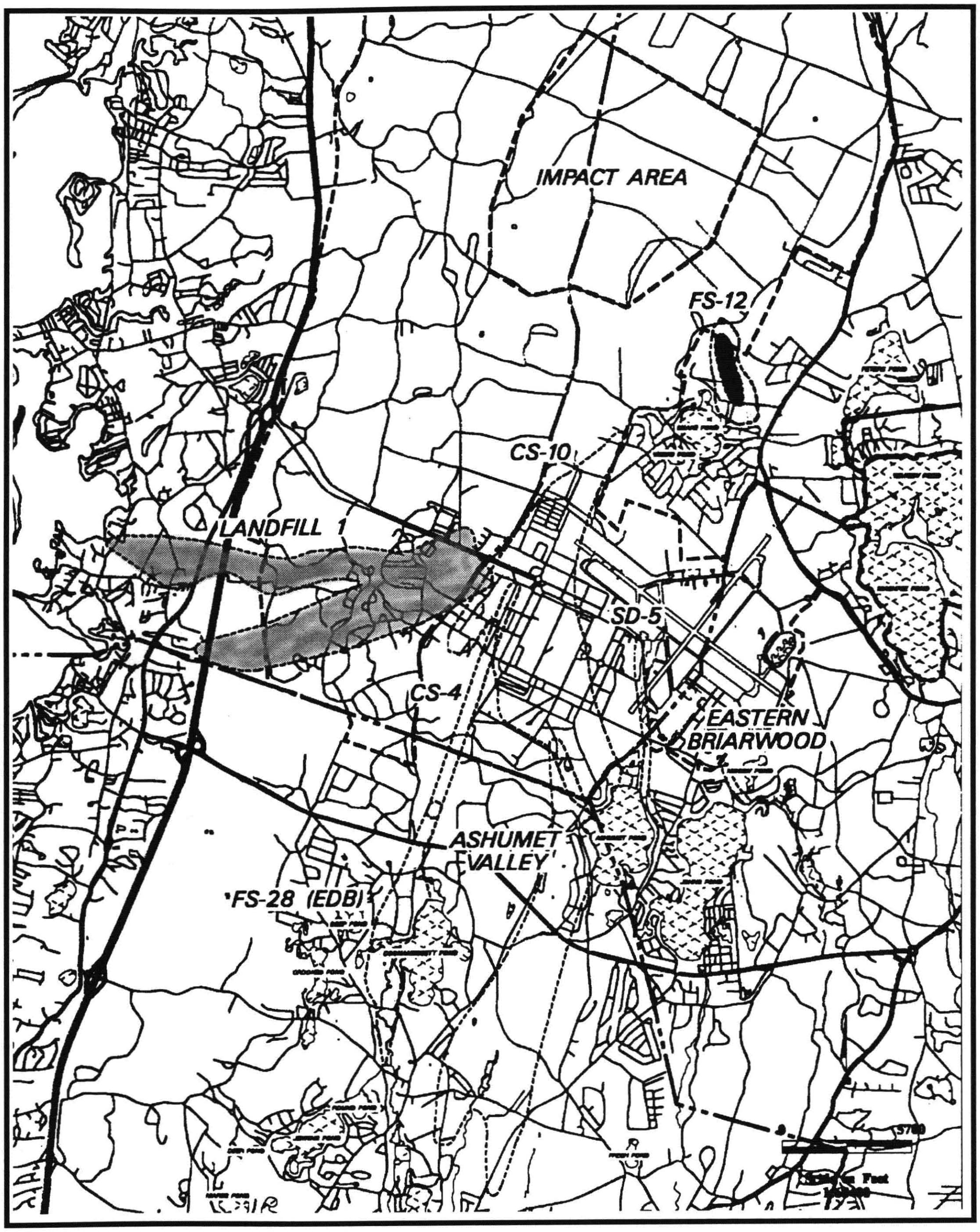


Figure 2-4, LF-1 Plume Map (MMR, 1997)

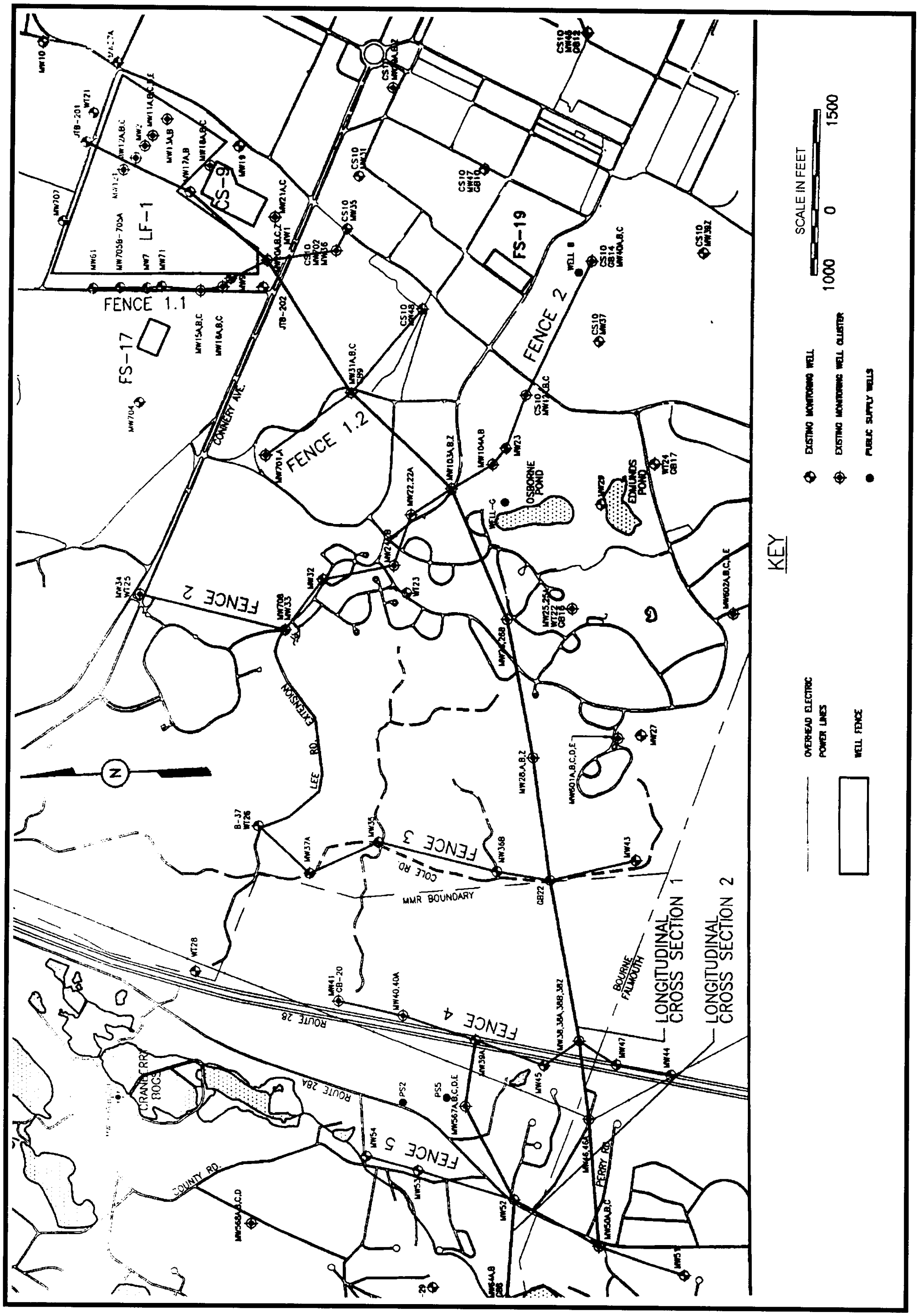


Figure 2-5, Area Map with Monitoring Well and Cross Section Locations (CDM, 1996)

3. USE OF HORIZONTAL WELLS

3.1 Description

Horizontal directional drilling (HDD) is a relatively new drilling technique, having its roots in the early 1970s. The drilling systems in use today in the environmental industry were developed from technologies utilized in the petroleum, the river crossing, the utility, and the mining industries. The systems include a drilling rig, navigational (guidance) equipment, and/or a solids control (drilling fluid) system.

Horizontal wells are installed by drilling a pilot borehole down from the surface at an angle until the desired depth is reached. A common rule of thumb is to have a 3:1 (vertical to horizontal) ratio for the depth of the well to the surface setback distance (Hodges, 1995). The borehole is then directed horizontally and inserted with drill pipe. The hole is either drilled as an inverted arc (i.e., with entry and exit points) or is drilled blind, meaning that it terminates in the subsurface (Figure 3-1).

When drilling inverted arc horizontal wells, the borehole is back-reamed, enlarging it to the desired diameter, and the drill pipe removed. Figure 3-2 shows a directional boring tool assembly and back-reaming assembly used in the environmental industry.

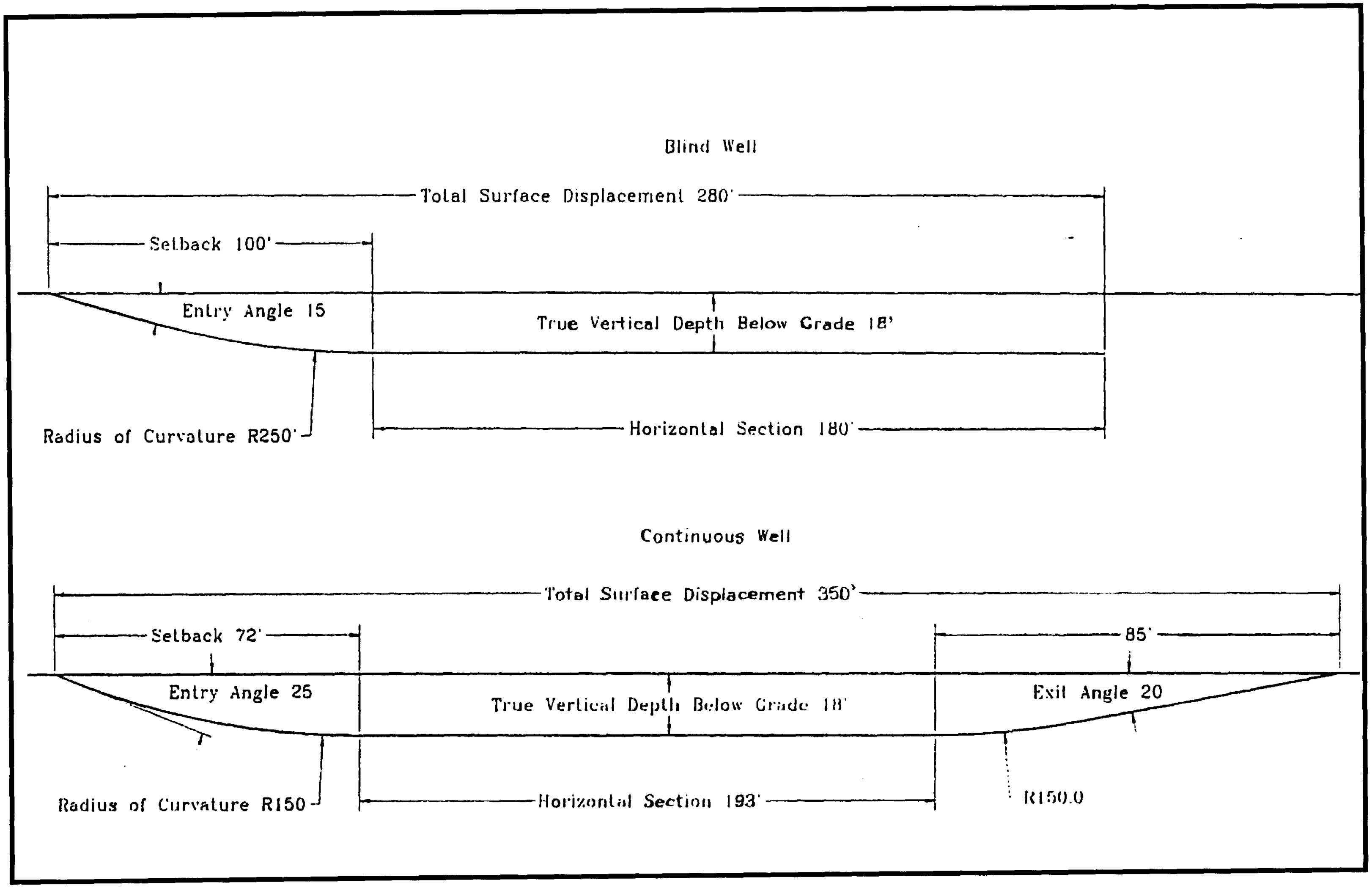


Figure 3-1, Blind and Inverted Arc Horizontal Wells (Hodges, 1995)

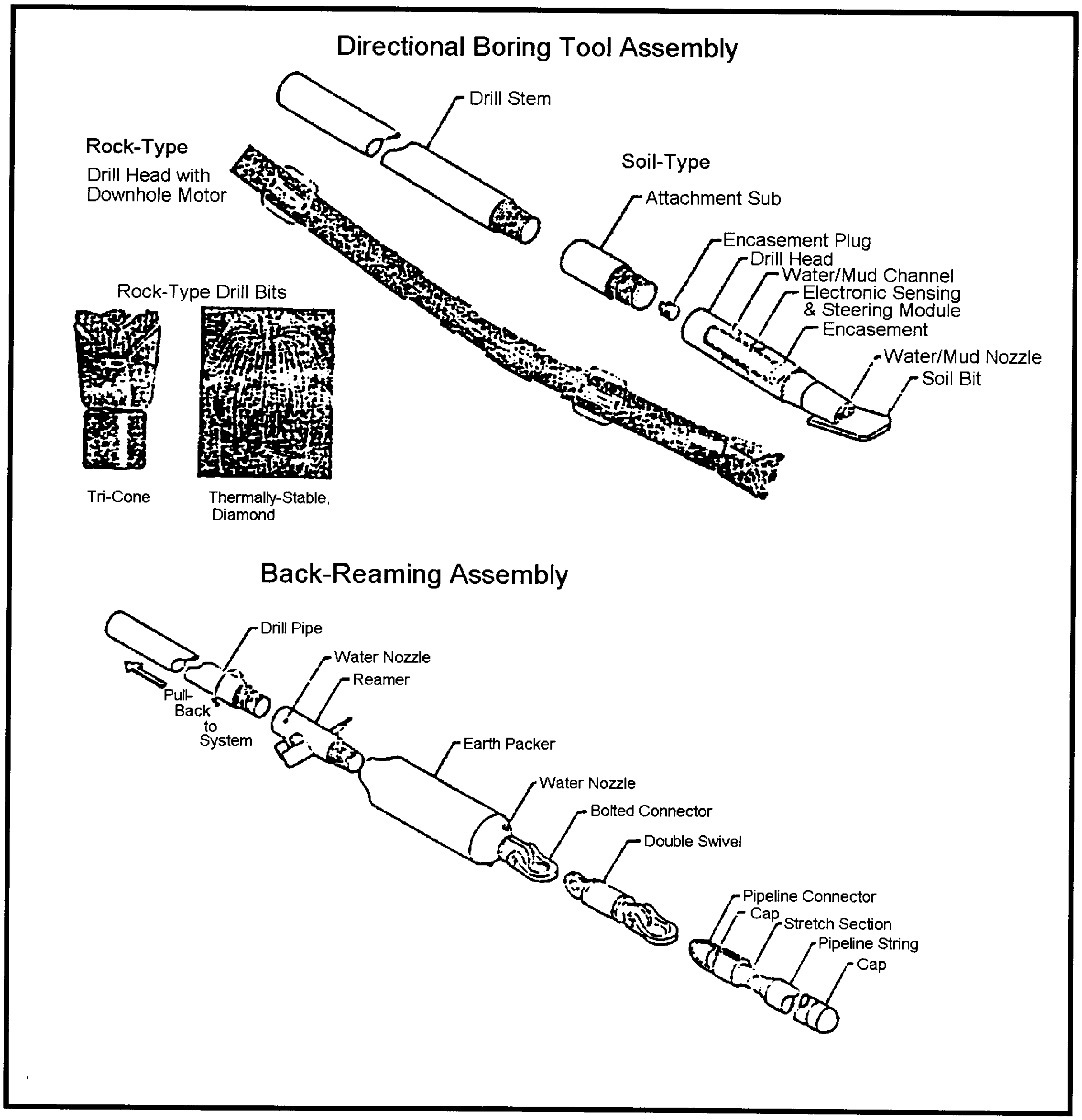


Figure 3-2, Directional Boring Tool and Back-Reaming Tool Assemblies (Hodges, 1995)

The borehole is simultaneously installed with well screen, which is attached, as the drill string is pulled back through the hole. Inverted arc horizontal wells are more cost-effective and easier to drill than blind wells. With blind wells, washover drilling techniques are required, wherein a larger diameter washover bit and drill pipe are drilled over the pilot drill string after the pilot borehole is completed. The pilot drill string is pulled out, leaving the drill pipe behind as temporary casing to stabilize the borehole (Hodges, 1995). A slightly larger diameter borehole than is required for the finished well results, and well screen is pushed through inside the drill pipe prior to removing the drill pipe (Russell, 1996). In general, horizontal wells can be drilled to within one to two feet of the target exit point over hundreds of feet of distance (Parmentier and Klemovich, 1996).

The first two horizontal remediation wells were drilled using a conventional petroleum industry mud rotary drilling rig in 1988 at the Department of Energy's innovative remediation technology demonstration site, the Savannah River Nuclear Facility, near Aiken, South Carolina. These wells were installed in order to evaluate their performance versus that of conventional vertical wells as components of soil vapor extraction (SVE), pump and treat, and other remediation systems. Two more horizontal wells were drilled at this site using a slant rig by 1990, and several more were drilled at other sites (including Tinker Air Force Base in Oklahoma) by 1991 with slant rigs and near surface horizontal drilling technology from the utility and pipeline river crossing industries (May, 1996, and Parmentier and Klemovich, 1996).

Over 200 horizontal remediation wells have been drilled in the United States and used for a variety of in situ remediation techniques, including groundwater extraction, SVE, air sparging, bioventing and in situ bioremediation, and non-aqueous phase liquid (NAPL) recovery. Several wells have been used in remediation systems which integrated more than one application. In addition, some wells were designed to be multi-purpose and perform more than one remediation task (Parmentier and Klemovich, 1996, and Wilson and Kaback, 1994). At John F. Kennedy International Airport in New York, for example, remediation activities to clean up spilled jet fuel included over 50 horizontal well installations, completed in April 1996, as components of SVE, air sparging, and bioremediation systems. Lengths of bores at JFK Airport ranged from 300 to 700 feet; and depths of wells ranged from three to five feet for SVE, and from 11 to 12 feet for air sparging. Screened intervals ranged from 70 to 500 feet (*Public Works*, 1996). Using horizontal wells at JFK allowed the airport to continue operations with minimal disruptions while the wells were drilled. This and other advantages are discussed in the next section.

3.1.1 Advantages of Horizontal Wells over Vertical Wells

Horizontal wells have several advantages over vertical wells. One advantage is that the screened length does not lie directly beneath the point of entry of horizontal wells. Thus they can be used in places that vertical access is restricted, such as underneath buildings, bodies of water, landfills, and storage tanks, or where the plume has migrated offsite. Horizontal wells are also preferable at sites where the drilling of vertical wells would necessitate an interruption in operations, such as airport runways, city streets, refineries, and chemical plants. For example, Figure 3-3 illustrates a horizontal well system under a driveway used to serve approximately 30 trucks daily. The system consists of a vapor extraction line and an air insertion line to remediate the contaminated soil beneath the packaging and shipping building, and a free product recovery line to contain the oil spilling out of the underground storage tank beneath the basement of the bakery. Vertical access to the two areas of concern was difficult at best, and would require a shutdown of operations at both the bakery and the packaging and shipping facility.

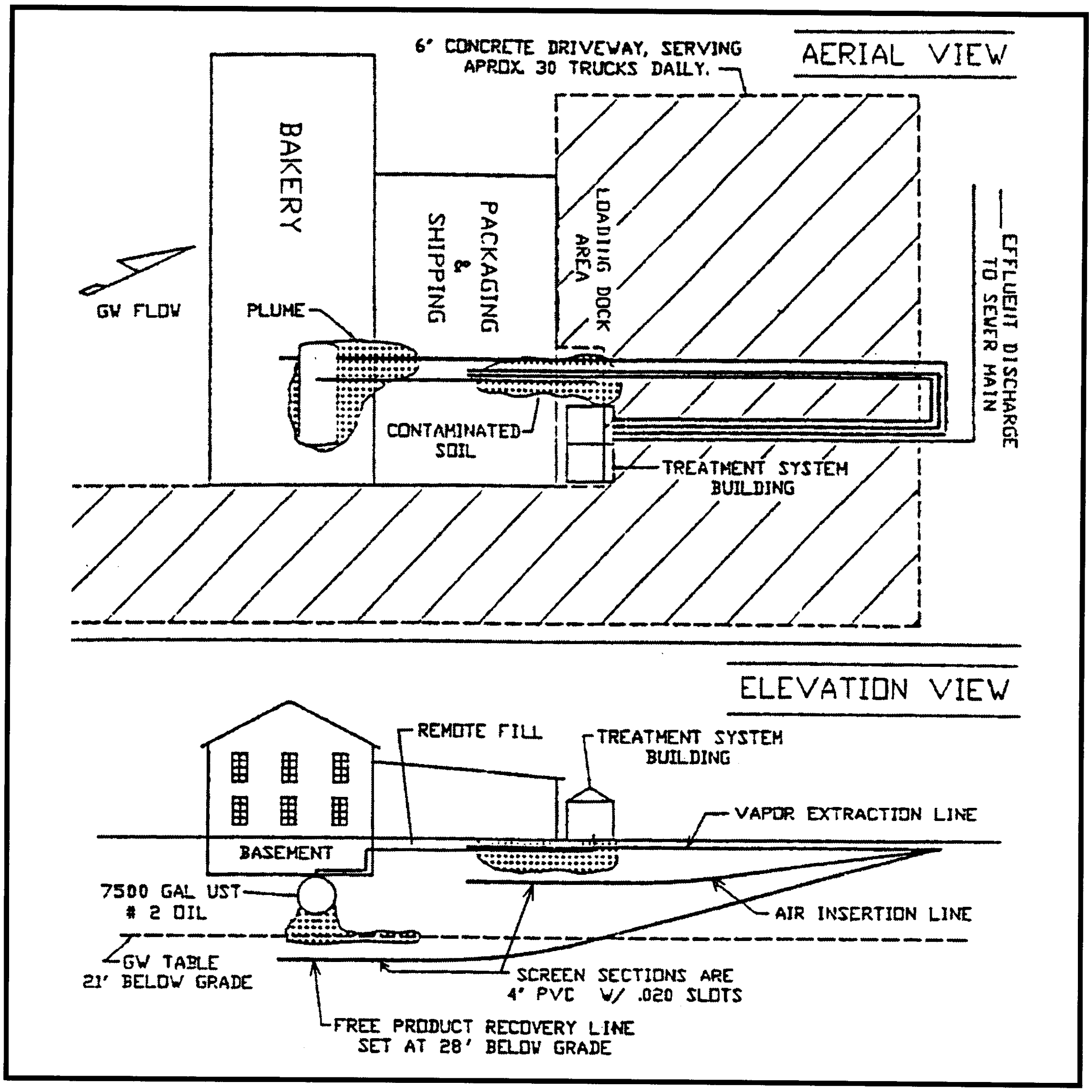


Figure 3-3, Horizontal Well System Under a Driveway (Hodges, 1995)

Subsurface soil and groundwater contamination is generally more of a horizontal than vertical problem because plumes migrate with groundwater flow, which is usually horizontal. Horizontal wells can be aligned with the principal plume axis for more efficient remediation. The greater efficiency is a result of a large, elongated zone of influence, a horizontally continuous capture zone, high specific capacity (a measure of the productivity of a well), and a long screen with low screen-entrance velocities (Karlsson, 1993). Flow patterns for both types of wells are illustrated in Figure 3-4.

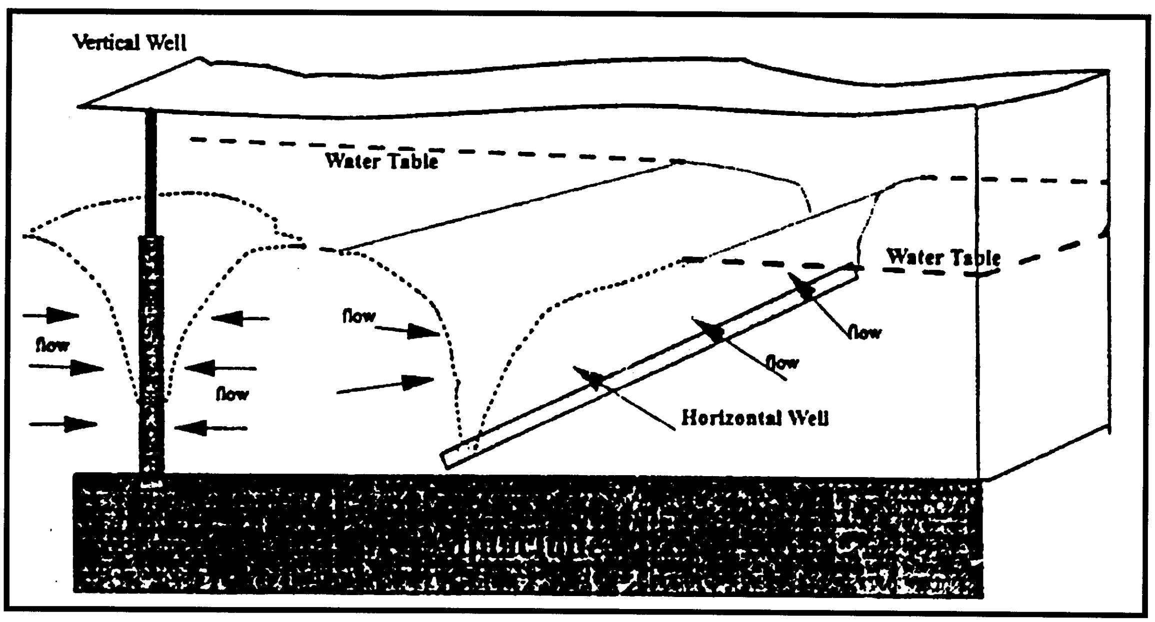


Figure 3-4, Flow Patterns of Vertical and Horizontal Wells (Russell, 1996)

Russell (1996) estimates that "for a given formation, the increase in efficiency [of horizontal wells over vertical wells] is directly proportional to the increase in well length in the formation." Thus a single horizontal well can replace several vertical ones. It was for this reason, along with the fact that the drilling would not interfere with surface operations, that Groundwater Technology, Inc., chose to use horizontal wells for remediation activities at a bulk fuel terminal in Los Angeles, California, in 1992 (Parmentier and Klemovich, 1996).

In another example, the plume may pass through soils with varying permeabilities. The horizontal well's continuous capture zone reduces the possibility of incomplete remediation attributable to capture zone gaps that may occur with vertical wells (May, 1994). In addition, a long zone of influence is more effective for hydraulic gradient control (i.e., pumping). For bioremediation, the increased surface area of horizontal wells allows more efficient delivery of nutrients, easier gas and water recovery, and minimizes formation clogging and plugging phenomena (Hazen et al., 1995). And the ability of horizontal wells to be located in any part of a formation, even along the bottom, can facilitate such activities as DNAPL recovery.

Although the cost of installing horizontal wells is at present much higher than the cost of installing vertical wells, the overall costs, including installation, of operating and maintaining a system that utilizes horizontal wells can be significantly lower. One reason for the higher cost of drilling horizontal wells is that there are relatively few contractors with the experience and ability to install them. However, as the use of horizontal wells becomes more widespread, the associated drilling costs should decrease over time.

It is apparent that horizontal wells have many advantages over vertical wells. However, there will be cases in which vertical wells are preferred over horizontal wells, especially if the total cost of using vertical wells at a particular site will be more economical.

3.1.2 Applications

Horizontal wells have a variety of environmental applications, including soil vapor extraction; use in traditional pump and treat remediation systems; air sparging; injection of bioenhancers for bioremediation; sampling for DNAPL investigation; vadose zone monitoring; and leachate collection. The LF-1 project group focused its investigation on the areas of bioremediation, PCE and TCE source investigation, and post-closure management. Therefore, the use of horizontal environmental wells for these applications are considered in this thesis.

3.1.2.1 Bioremediation

During the natural degradation process, or biodegradation, contaminants are destroyed by bacteria which break down the toxic compounds into nontoxic by-products. Because the natural process is often very slow and may not be effective for certain compounds, it was necessary to develop techniques, commonly termed bioremediation, to enhance the process in order to utilize it for environmental remediation. The most common factors regulated in this process are the concentrations of limiting nutrients, such as nitrogen, phosphorus, molecular oxygen, and moisture. Where it is feasible, bioremediation is among the least expensive cleanup technologies. Because contaminants are destroyed and not merely moved to another site or immobilized, costs, risks, and time are reduced. In addition, public and regulatory acceptance is greater (Litchfield, 1993).

Biodegradation occurs either aerobically (requiring the presence of oxygen) or anaerobically (requiring the absence of oxygen). Whether a given compound will degrade, and how efficiently, depends on the condition (oxidized or anoxic) of the environment and the presence of the appropriate bacteria (aerobic or anaerobic) and their necessary nutrients. For example, the LF-1 plume is composed mainly of the chlorinated solvents PCE, which is best remediated anaerobically, and TCE (incidentally a biodegradation by-product of PCE), which is more efficiently removed by aerobic bacteria.

In situ bioremediation using methanotropic (methane-oxidizing) bacteria was demonstrated at the Savannah River Site, Aiken, South Carolina, in 1992 on soil and groundwater impacted by chlorinated solvents, namely PCE and TCE. A methane/air mixture was injected into a horizontal well located in the saturated zone, and vapor was extracted from a parallel horizontal well in the vadose zone (Figure 3-5).

This layout not only stimulated biodegradation activity, but hindered the spread of the plume during the test. Biweekly groundwater monitoring for several weeks from 13 wells showed a simultaneous increase in bacteria and decrease in concentrations of PCE and TCE in groundwater and soil gas. The rate of bacteria increase was as high as more than one order of magnitude for some sampling events, and PCE and TCE concentrations in groundwater decreased from approximately 10,000 parts per million (ppm) by as much as 99% in less than six weeks in some wells (Hazen et al., 1995).

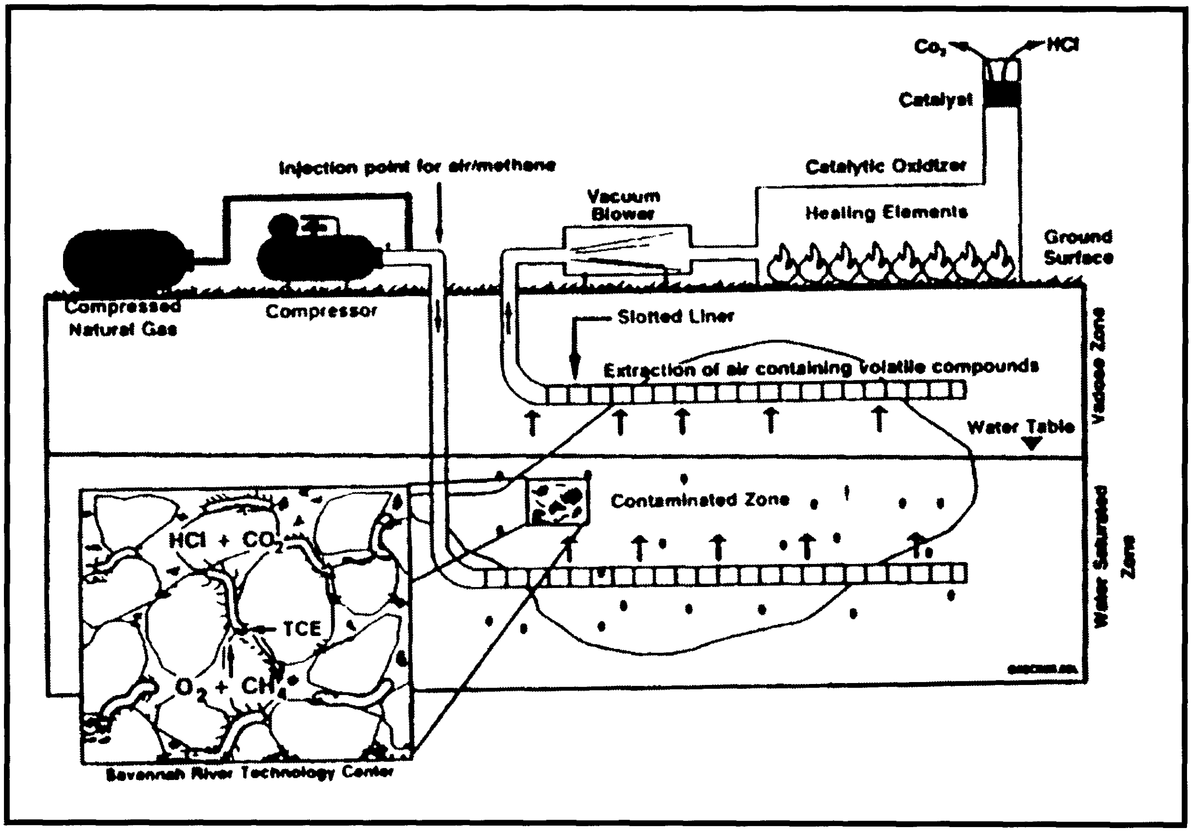


Figure 3-5, Bioremediation at the Savannah River Site (Hazen et al., 1995)

The concentrations of PCE and TCE at LF-1 are relatively low—the maximum concentrations are on the order of 65 μg/L, or ppb. Thus, the reduction in contaminant concentrations at LF-1 will not be as dramatic as that which took place at the Savannah River Site. The bioremediation system design proposed for LF-1 involves the creation of a series of alternating aerobic and anaerobic biozones roughly perpendicular to the plume along its length for a two-stage remedial approach (Haghseta, 1997). Contaminated groundwater will first flow through an aerobic biozone, where TCE and other less chlorinated compounds in the plume will be treated, and then through an anaerobic biozone, where PCE and other VOCs will be broken down into less chlorinated forms.

The requirements for the aerobic biozones include the injection of pure oxygenated water to create or maintain aerobic conditions, methane as the primary growth substrate, and ammonium and phosphate as nutrients to stimulate bacterial growth. For the anaerobic biozones, methanol, the recommended primary growth substrate, and ammonium and phosphate, the nutrients, will be added, with no additional oxygen injected. The higher BOD (biochemical oxygen demand) in the anaerobic biozones resulting from the heightened bacterial population will be sufficient to create and maintain anaerobic conditions.

These biozones can be created using either vertical or horizontal wells. Figure 3-6 illustrates the proposed configuration for the vertical well system, and Table 3-1 summarizes various parameters (radius of influence of the wells, contaminant concentrations, required injection rates, and total bioremediation time) of the design.

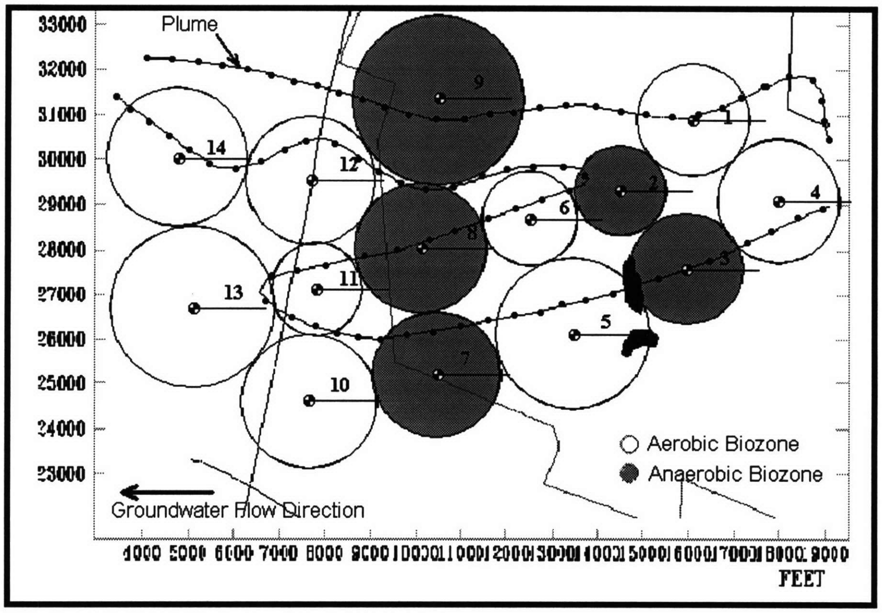


Figure 3-6, Proposed Bioremediation Scheme (Haghseta, 1997)

Table 3-1, Summary of Bioremediation Design

Well ID	Radius of Influence (ft)	Contaminant Concentration (µg/L)	Required Injection Rate (gpm)	Approx. Total Bioremediation Time (years)
1 (MW701A)*	1,500	64	2,128	7.7
2 (MW22)*	720	65	613	13.9
3 (MW23)*	960	65	999	13.9
4 (near MW48)	1,200	64	1,475	7.7
5 (near Edmunds Pd.)	1,500	10	2,128	5.7
6 (near WT23)	1,500	10	2,128	5.7
7 (MW43)*	1,320	30	1,717	11.2
8 (near MW36B)	1,320	30	1,717	11.2
9 (WT26)*	1,800	48	2,809	12.8
10 (MW44)*	1,500	26	2,128	6.8
11 (near MW45)	960	26	999	6.8
12 (near MW40)	1,080	10	1,241	5.7
13 (MW52)*	1,500	0	2,128	n/a
14 (near MW5)	1,200	0	1,475	n/a

Modified from Haghseta (1997).

Notes: Existing wells are designated with an asterisk.
n/a: not applicable (contaminant concentration is 0 µg/L at these wells).

A total of six biozones are proposed. Wells 1 and 4 form aerobic biozone 1, wells 5 and 6 form aerobic biozone 2, wells 10, 11, and 12 form aerobic biozone 3, and wells 13 and 14 form aerobic biozone 4. The purpose of the final aerobic biozone is to prevent any high levels of contamination from bypassing treatment and reaching the bay. Wells 2 and 3 form anaerobic biozone 1 and wells 7, 8, and 9 form anaerobic biozone 2. The aerobic biozones are 5,400 feet, 6,000 feet, 7,080 feet, and 5,400 feet long, respectively, and the anaerobic biozones are 3,360 feet and 8,880 feet long, respectively. This design utilizes a total of 14 wells, seven of which already exist. Assuming that horizontal wells would be installed in approximately the same locations, a minimum of 10 horizontal wells would be needed to supplement the existing wells. Placement is discussed in Section 3.2.3.

At first glance, it would seem impractical to utilize horizontal wells in the design since they are more expensive to install than vertical wells. However, Haghseta (1997) concluded that her proposed design was not feasible due to the high injection rates required for the individual wells (613 gpm to 2,809 gpm). This could possibly be mitigated either by using more than seven additional vertical wells, thus reducing the individual required pumping rates for each well, or by using horizontal wells (either alone or in combination with existing vertical wells), which require lower injection rates than vertical wells. Another way to reduce the injection rates is to inject the bioenhancers in the gaseous, rather than liquid, phase (Haghseta, 1997).

Depending on existing dissolved oxygen concentrations, air (approximately 20% oxygen), pure oxygen, or hydrogen peroxide can be injected if existing levels are deficient at the locations where aerobic biozones are desired. In order to create anaerobic zones, it will be necessary to inject only nutrients and substrates—no oxygen—to stimulate growth. Due to the oxygen demand of the increased bacterial population, the zone will soon become fully anaerobic. In any case, a more detailed design will require the assessment of oxygen levels at the proposed locations.

Two problems have traditionally been associated with in situ bioremediation: biofouling and channeling. The term biofouling describes the clogging of systems and their subsequent loss of efficiency due to the proliferation of bacteria. In this case, the system component of concern is the slotted well screen, which can be cleaned with chemicals or by developing the well. Wells are usually developed after installation to create a natural gravel pack around the screen by removing fines from the aquifer, thereby increasing the efficiency of the intake. The same principles can be utilized to "unclog" well screens that have become biofouled. Horizontal wells can be developed by pumping, jetting, swab/surging, or a combination of the preceding.

Channeling describes the process whereby preferential pathways develop in a formation from fluid injection. Channeling can be mitigated by injecting the fluid slowly and through fine apertures. This results in smaller bubbles which travel more freely through pore spaces, reducing the development of continuous pathways.

3.1.2.2 PCE and TCE Investigation

One part of the LF-1 group project is the investigation of the presence of a PCE and TCE source, possibly in the form of dense nonaqueous phase liquids (DNAPLs), at the site. The prevailing assumption is that the contaminants entered the aquifer in a dissolved, rather than separate phase, state. This assumption has not been confirmed since no vertical wells can be placed directly where the contamination occurred due to the possible presence of live ordinance in the landfill, and no testing has been performed to determine the existence of a contaminant source under the landfill. Obviously, the installation of a horizontal well would have made it possible to verify the above assumption. In this case, however, the relatively high cost of drilling horizontal wells precludes this option unless the well could also be used to remediate the DNAPLs (if any), thereby justifying the expenditure.

Therefore, calculations were made, based on estimates from interviews and record searches of the types and quantities of wastes that were disposed of in the landfill, in order to determine if the estimated quantities of solvents could have generated the concentrations in the plume. The initial calculations showed that either a DNAPL source exists, or that the contaminant is mixed with other chemicals that in effect increase the contaminant's natural retardation factor. Further calculations, which take the effects of contaminant mixing into account, indicate that the source probably no longer exists (Kostek, 1997).

Nonaqueous phase liquids (NAPLs) are sparingly soluble in water. Thus, the chemical pools in the aquifer and then spreads laterally in the general groundwater flow direction. Light nonaqueous phase liquids (LNAPLs), such as petroleum hydrocarbons, float on top of the water table, and DNAPLs, such as chlorinated solvents, sink until reaching a relatively impermeable stratum. As the NAPL pool migrates through the soil, residual blobs of the NAPL become trapped in the pores under the influence of capillary forces. Unless buoyant and/or viscous forces can overcome capillary forces, the NAPL will remain trapped. For this reason, residual NAPLs are difficult to remediate, especially with traditional pump and treat systems.

NAPL pools can be removed via total fluids recovery. Two residual DNAPL remediation techniques that can be performed using horizontal wells are air sparging, in which injected air flowing upward through the saturated zone volatilizes contaminants and carries them into the vadose zone for vapor extraction treatment, and soil flushing. Air sparging has been shown to be effective in cleaning up entrapped VOCs, especially when horizontal wells are used (Figure 3-7).

A horizontal well system utilized for DNAPL remediation at the Savannah River Site was five times more efficient than a vertical well system at the same site (National Research Council [NRC], 1994a). In addition, the horizontal well system cost almost 50% less than a conventional pump-and-treat/SVE system (NRC, 1994a). An incidental benefit of air sparging is that the increased oxygen supply promotes bioremediation, further increasing the efficiency of this technology.

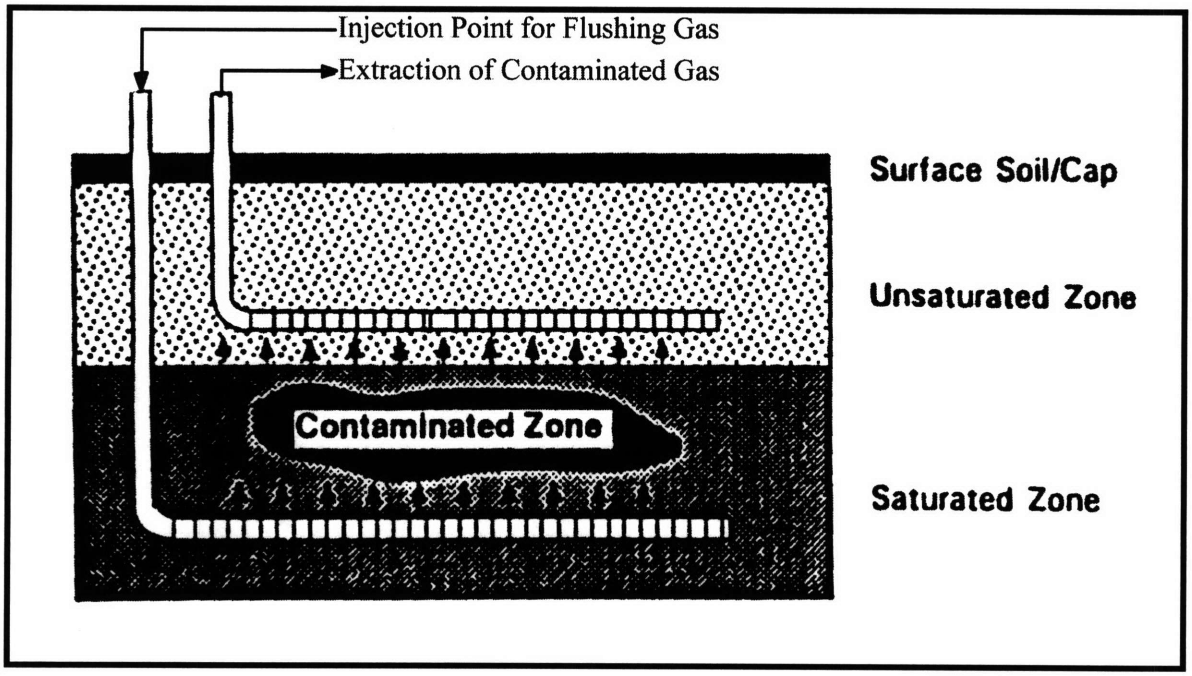


Figure 3-7, Air Sparging of NAPLs with Horizontal Wells (NRC, 1994a)

Soil flushing increases the amount of contaminants recovered with pump-and-treat systems by mobilizing contaminants which have low water solubility, are in NAPL pools or globules, or are sorbed onto soil particles. Cosolvents and surfactants both mobilize NAPL globules by increasing contaminant solubility. Surfactants also mobilize by reducing NAPL-water interfacial surface tension or NAPL viscosity.

3.1.2.3 Post-closure Management

The purpose of the post-closure management plan for the LF-1 landfill cover system is to insure the integrity of the cover system for an extended period of time, and to diminish the possibility of the capped cell contributing to further groundwater contamination (León, 1997). The plan includes a groundwater and surface water monitoring plan and a program for air quality monitoring. At the LF-1 site, sufficient monitoring wells already exist that can be incorporated into the plan; therefore, the installation of additional, horizontal wells for the sole purpose of groundwater monitoring would not be necessary. However, should the groundwater monitoring plan indicate that leaching of contaminants into the underlying aquifer occurs despite the cover system, horizontal wells can be a very cost-effective way to retroactively install a leachate collection system. Horizontal wells were recently used successfully for this task at the Livingston County landfill near Pontiac, Illinois (*Ground Engineering*, 1997).

3.1.3 Drilling Systems

There are several types of horizontal directional drilling systems available for environmental applications, ranging from very sophisticated to relatively simple. For the purposes of environmental remediation, these systems can be grouped into three categories: small, medium, and large. Small rigs typically have a turning radius of less than 100 feet and are usually used for utility installations. Medium rigs, which are the most common in the environmental industry, have a turning radius of 300 to 1,000 feet with a typical value of 600 feet, and a build angle (rate of change of direction) of 6 to 20 degrees per 100 feet of length. Large rigs are most commonly used for pipeline and river crossing installations. They have a turning radius ranging from 1,000 to 3,000 feet and a build angle of 2 to 6 degrees per 100 feet of length. The major differences between the various types of systems are in the areas of guidance/navigational systems, drilling fluid systems, drill rig power and capabilities, and drilling methods (May, 1994, and Hodges, 1995).

3.1.3.1 Guidance/Navigational Systems

Guidance systems direct the drill bit and track its location. The systems vary in complexity from simple radio systems for shallow depths to sophisticated downhole electromagnetic guidance systems for deep drilling.

For environmental purposes, a radio-frequency guidance system with walkover receiver and tracker is generally used for guiding the horizontal borehole where surface obstacles, such as buildings or roadways, are not a factor, and where the depth of the well is less than approximately 40 feet. This system supplies depth, toolface (i.e., the angle between the projection of the bend axis and the high side of the hole on the hole bottom), and pitch to a receiver operated by a tracker on the surface above the path of the borehole. The radio-frequency guidance system is accurate to within 5% of the actual path (Hodges, 1995).

The radiosonde device, a miniature radio transmitter which measures and transmits data, is widely used to track the location of the drill bit. The intensity of the transmitted downhole radio signal as the receiver is walked back and forth over the surface indicates the location of the borehole. These devices transmit information, rather than guide the drill bit, and therefore crooked boreholes tend to result if used alone (May, 1994).

Where surface obstacles may pose a problem, electromagnetic telemetry guidance systems can be used. These wireless measurements while drilling (MWD) systems transmit real-time telemetry of all necessary data through the drill pipe to a transducer for location and orientation of the drill head and well coordinates within 1% accuracy (Hodges, 1995). This system is also used for deeper wells and for steerable motor drilling.

Steering tools, which utilize a series of magnetometers and accelerometers to provide the location signal that gives elevation, inclination, and azimuth readings, are very widely used. While very accurate (±2° for azimuth and ±2% for vertical depth to 50 feet), such devices are north-referencing tools (May, 1994). Thus they can be influenced by magnetic forces from objects such as piles, tanks, and other buried ferrous metal objects. Surface verification systems which create their own magnetic field may be used to determine the magnetic influences on the downhole steering tool.

Gyroscopic systems, which are not influenced by magnetism, include single-shot and multi-shot systems. Single-shot systems are so called because only one point of measurement is recorded during a measuring process. These systems are used to orient directional drilling sets and to check individual measurement operations. Multi-shot systems record multiple measurement points during a measuring process and are used to determine the borehole's course.

3.1.3.2 Solids Control Systems

The purpose of drilling fluid is to stabilize the borehole, remove the cuttings, and lubricate the borehole. In addition, the drilling fluid must not spread existing contamination, add new contamination, or reduce the well's remediation effectiveness (Karlsson, 1993). According *Public Works* magazine (1996), "experienced drillers recognize [that] drilling fluid often means the success or failure of a job."

Solids control systems range from expensive, large ones (capable of pumping up to more than 500 gpm) that recirculate the fluid out of the borehole in order to remove the cuttings, to inexpensive, small, simple systems (5 to 10 gpm) which force the fluid/cuttings into the borehole walls, thereby damaging the surrounding formation. A closed-loop, recirculating solids control system with pumping rates up to 150 gpm is commonly used for the drilling of horizontal remediation wells (Hodges, 1995).

For environmental purposes, a drilling fluid should ideally form a thin, removable, impermeable layer on the hole wall that not only helps provide stability to the hole through positive pressure in the drilling fluid, but keeps fluid and cuttings out of the formation, thus preventing the spread of contamination and minimizing reductions to the formation's permeability (Karlsson, 1993).

Because cuttings must be removed from the borehole to keep damage of the surrounding formation to a minimum, the drilling fluid must be circulated. Unlike the case of vertical wells, in which viscosity alone is utilized, fluids used in the drilling of horizontal wells must rely on both viscosity and turbulence to prevent cuttings from collecting at the bottom of the borehole. According to Reynold's number, turbulence is inversely proportional to the density or viscosity; therefore, a fluid with low density and viscosity will give the best results. However, the fluid must also have sufficient gel strength so that cuttings will not settle out when pumping stops (Russell, 1996).

Bentonite-based drilling fluids, which are commonly used for utility installations, are often not appropriate for environmental work because they can damage the surrounding formation and clog the screen slots (*Public Works*, 1996). Although more expensive, guar gum and polymer drilling fluids are more suitable. For example, Baroid Industrial Products' Bio-Bore™, a proprietary polymer blend, was used at the JFK Airport project mentioned in Section 3.1 (*Public Works*, 1996). Other proprietary polymer-based drilling fluids include InstaPac and EZ Mud. These special drilling fluids are biodegradable and are destroyed by natural bacteria within one to three days. However, increase in biological growth leading to biofouling of the well screen has been observed with the use of these drilling fluids, making additional cleaning and well development necessary (Russell, 1996).

If the natural formation contains a moderate or greater fraction of clay, the borehole can be drilled with water as the drilling fluid, which is then recycled through the solids control system. If the soil is very sandy or similarly unstable, a very low solids bentonite or organic or synthetic polymer drilling fluid is appropriate (Hodges, 1995).

3.1.3.3 Drill Rig Power and Capabilities

Drill rig power requirements become less crucial to the success of the drilling operation when one has good navigational equipment to produce a straight (i.e., not too crooked) borehole, and a good solids control system to provide adequate lubrication and borehole stability. These factors lead to greater ease of installation. Drill rig capabilities are rated by such factors as total drilling distance and borehole diameter, and correlate with drill rig power (measured in terms of thrust/pullback and maximum torque).

Small rigs have less than 15,000 lb of thrust/pullback and a maximum torque less than 2,000 ft-lb (May, 1994). Assuming a nominal 12-inch borehole (the maximum for small rigs), they can drill over distances up to 700 feet and handle drill pipe in sections of five-to ten-foot lengths. Small rigs are generally wheel-mounted, have good maneuverability, and are the least expensive.

Medium rigs are generally track-mounted and also have good maneuverability. They have thrust/pullback ranging from 40,000 to 100,000 lb and maximum torque ranging from 2,000 to 20,000 ft-lb. For a 12-inch borehole, these rigs are capable of drilling wells utilizing drill pipe in 10- to 30-foot sections over distances of 700 to 2,000 feet (May, 1994).

The drilling distance of large rigs can exceed 2,000 feet for 12-inch boreholes. They can handle drill pipe in 30- to 40-foot lengths and are usually trailer-mounted. The thrust/pullback of large rigs can be greater than 100,000 lb and the maximum torque greater than 20,000 ft-lb (May, 1994).

The borehole must be large enough to allow the well screen to be pushed or pulled through without compromising its structural integrity. Boreholes drilled for the installation of environmental wells are generally in the 12-inch (give or take two inches) diameter range. The rigs mentioned in this section are all capable of achieving this diameter. However, this ability is useless if the rig does not have sufficient power to install the screen.

3.1.3.4 Drilling Methods

Several different methods can be used to drill horizontal wells; not all of them are appropriate for environmental purposes. The most common method for drilling horizontal remediation wells is a low-pressure, fluid-assisted, rotary drilling process. For heterogeneous soils, long drilling distances, and wells installed in rock, drilling may be accomplished using a steerable downhole air hammer, air rotary, or mud motor assembly.

Two principal types of mud motors can be used for HDD: turbines or positive displacement motors. Because turbines work best at rotary speeds which are too high for most bits, positive displacement motors are generally preferred for environmental work. Rotary systems are best suited for homogeneous formations.

Hammer (percussion) and air rotary drilling work is primarily used in heterogeneous soils containing boulders or coarse gravel and highly indurated or fractured rock formations. Moling and jetting are the simplest and least expensive methods, but cannot be used for environmental purposes due to the resulting formation damage. Moling works best in soft, compressible soil. In this technique, a rotating bit compresses soil into a narrow (a few inches in diameter) borehole wall and does not generate cuttings. Jetting systems utilize a high pressure water jet and produce cuttings which are mixed with drilling fluid and compressed into the borehole wall. The subsurface at the MMR is composed mainly of sandy soils and is generally considered to be homogeneous. Therefore, rotary drilling using a positive displacement motor is recommended at the LF-1 site.

3.1.3.5 Summary of Drilling Systems

Table 3-2 summarizes the general features of small, medium, and large rigs.

Table 3-2, Summary of General Drill Rig Features

Features	Small	Medium	Large
Turning Radius	100-300 ft	300-1,000 ft	1,000-3,000 ft
Application	utility installations	environmental, river crossing	oil or gas drilling
Drilling Method	jet hammer, moling	rotary drilling	rotary, percussion drilling
Build Angle		6° to 20°/100 ft length	2° to 6°/100 ft length
Thrust/Pullback	<15,000 lb	40,000-100,000 lb	>100,000 lb
Max. Torque	<2,000 ft-lb	2,000-20,000 ft-lb	>20,000 ft-lb
Drill Pipe Length	5-10 ft joints	10-30 ft joints	30-40 ft joints
Drilling Distance	<700 ft	700-2,000 ft	>2,000 ft
Power Source	<150 hp	150-250 hp	>250 hp
Mounting	wheel-mounted	track-mounted	trailer-mounted

Modified from May (1994).

3.2 Drilling Plan for LF-1 Remediation

The main focus of this drilling plan concerns the use of horizontal wells at LF-1 for bioremediation. Several factors must be considered when drilling horizontal wells. These include site-specific criteria, such as site surface conditions, subsurface conditions, and hydrogeology; selection of well materials and drilling systems; and placement and number of wells.

3.2.1 Site-specific Criteria

As mentioned above, horizontal directional drilling is a complex undertaking due to the nature of subsurface work and site characterization is an important part of any drilling plan. This section details the Main Base Landfill's surface site conditions, subsurface stratigraphy, and hydrogeology.

3.2.1.1 Surface Site Conditions

Elevations in the northern portion of the MMR, in which the Range Maneuver and Impact Area is located, range from 100 to 250 feet above sea level. The landfill, located in the southern portion of the Range Maneuver and Impact Area, occupies approximately 100 acres of relatively flat, open to heavily wooded terrain. The Range Maneuver and Impact is undeveloped and covered mainly by forest classified as pine-oak climax. A perimeter fence along Herbert Road, Turpentine Road, and Connery Avenue was installed as part of closure activities for the 1970 and Post-1970 Cells and the Kettle Hole (Figure 2-3). Locked gates limit access to Herbert Road.

Closure plans for LF-1 were finalized and executed in May 1993 and August 1993, respectively. Closure activities for the 1970 and Post-1970 Cells and the Kettle Hole included capping these areas. Activities for the 1970 and Post-1970 Cells and the Kettle Hole complied with the Massachusetts Solid Waste Management Regulations (310 CMR 19.000), indicating that these areas were covered with at least 12 inches of soil capable of supporting vegetation on the surface. At the same time, a different closure plan, consisting of leaving buried wastes in place beneath the existing vegetation and soil cover, and performing groundwater monitoring and surface maintenance for the next 30 years, was implemented for the Northwest Operable Unit (NOU).

3.2.1.2 Subsurface Stratigraphy

The stratigraphy of the western Cape Cod area has been documented by the US Geological Survey, outside consultants, and the MMR itself. Data were collected from several borings drilled during monitoring well installation activities (Figure 2-5). Geologic cross sections were created from available data; selected sections are included as Figures 3-8 through 3-13 (CDM, 1996). As stated in the Final Remedial Investigation Report (CDM, 1996), the data were widely spaced. Consequently, the stratigraphy is most likely much more complex than is shown on the figures.

The soils in the area of concern consist primarily of Mashpee Pitted Plain and/or Buzzards Bay Moraine overlying a layer of glacio-lacustrine sediment deposits which forms the base of the local unconfined aquifer system (Figure 3-14). The Mashpee Pitted Plain (MPP) outwash is on average approximately 200 feet thick in the landfill area and overlies a thin layer of glacio-lacustrine sediment (GLS) deposits. Beneath the LF-1 source area, the GLS is underlain by coarse sand and gravel, while further downgradient (westward toward Buzzards Bay), the GLS is underlain by till or bedrock. Beyond, or just west of, this area (near well fence 1.2), the Buzzards Bay Moraine (BBM) begins where the MPP outwash ends. The GLS does not continue beneath the BBM just east of well fence 3. MPP, GLS, and BBM soils were deposited between 7,000 and 85,000 years ago during the retreat of the Wisconsin stage of glaciation. The glaciation process is discussed in detail by Wagle (1997).

The MPP is comprised of clean, fine to coarse sand and gravel overlying clean, medium to fine sand, which in turn overlies silty fine to very fine sand. According to the Remedial Investigation Report (CDM, 1996), the MPP outwash contains on average 6.5% fines (silt and clay). The values ranged from 1 to 86% and most samples containing less than 5% fines, which indicates that the outwash material is relatively well sorted (CDM, 1996). The mean median grain size, d_{50}, of the samples was approximately 0.5 mm, indicating that the material in this layer is relatively coarse (CDM, 1996).

The base of the aquifer is a relatively thin, fine-grained layer of GLS deposits consisting of laminated silts, clays, and fine sands. The average fines content of the GLS was found to be 23%, and d_{50} was 0.17 mm. Under LF-1, the GLS is underlain by coarse sand and gravel (CDM, 1996).

As stated by Wagle (1997), the BBM is complicated and poorly characterized. However, it is known that the soils comprising the BBM range from well-sorted coarse sand and gravel to dense, very poorly sorted fine to coarse sand, gravel, silt, and clay. The percentage of fines averages 15% and varies from 1 to 89%. The mean d_{50} was found to be approximately 0.4 mm. This indicates that the soils of the BBM are finer and more poorly sorted than those of the MPP (CDM, 1996).

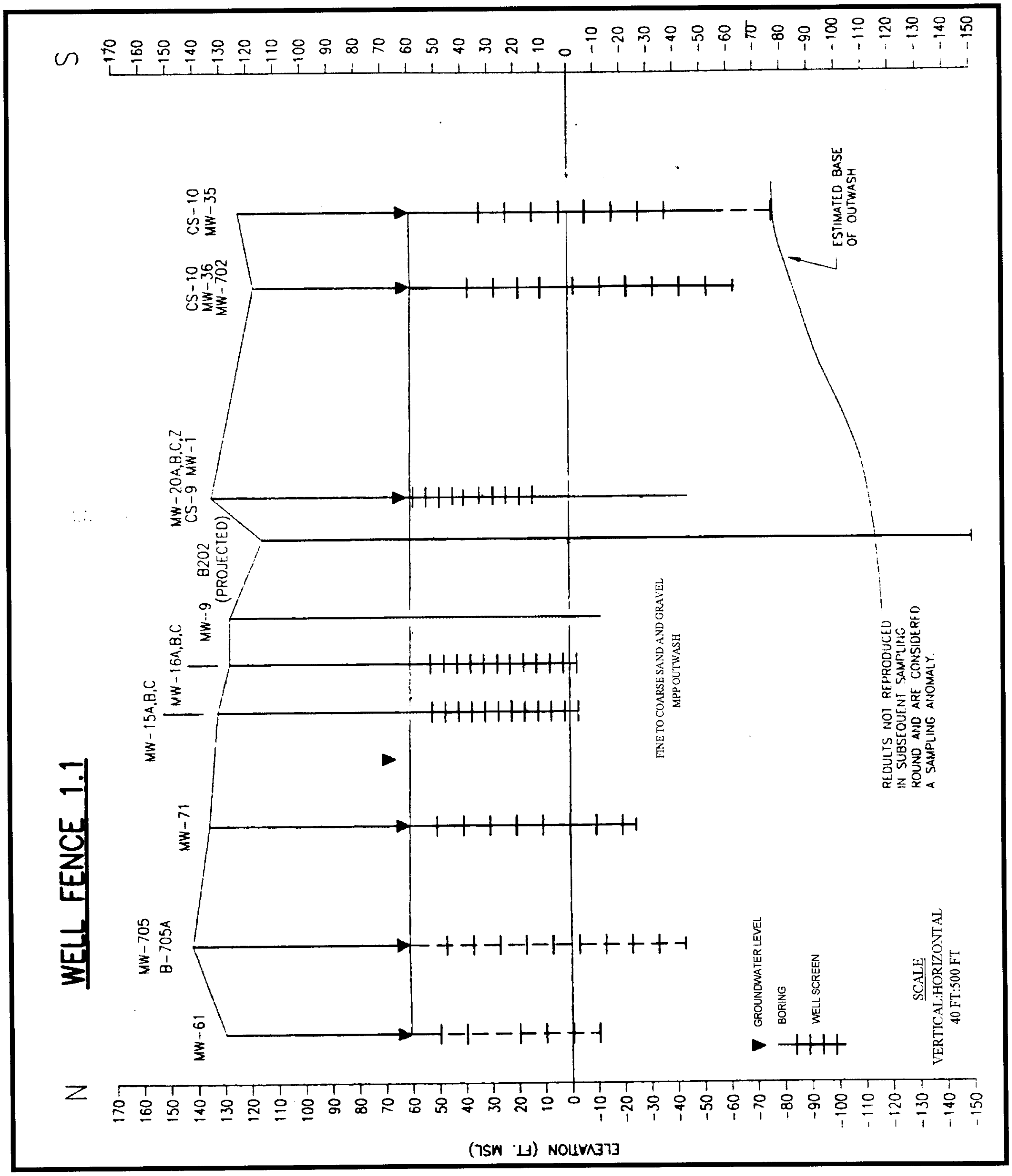


Figure 3-8, Well Fence 1.1 (CDM, 1996)

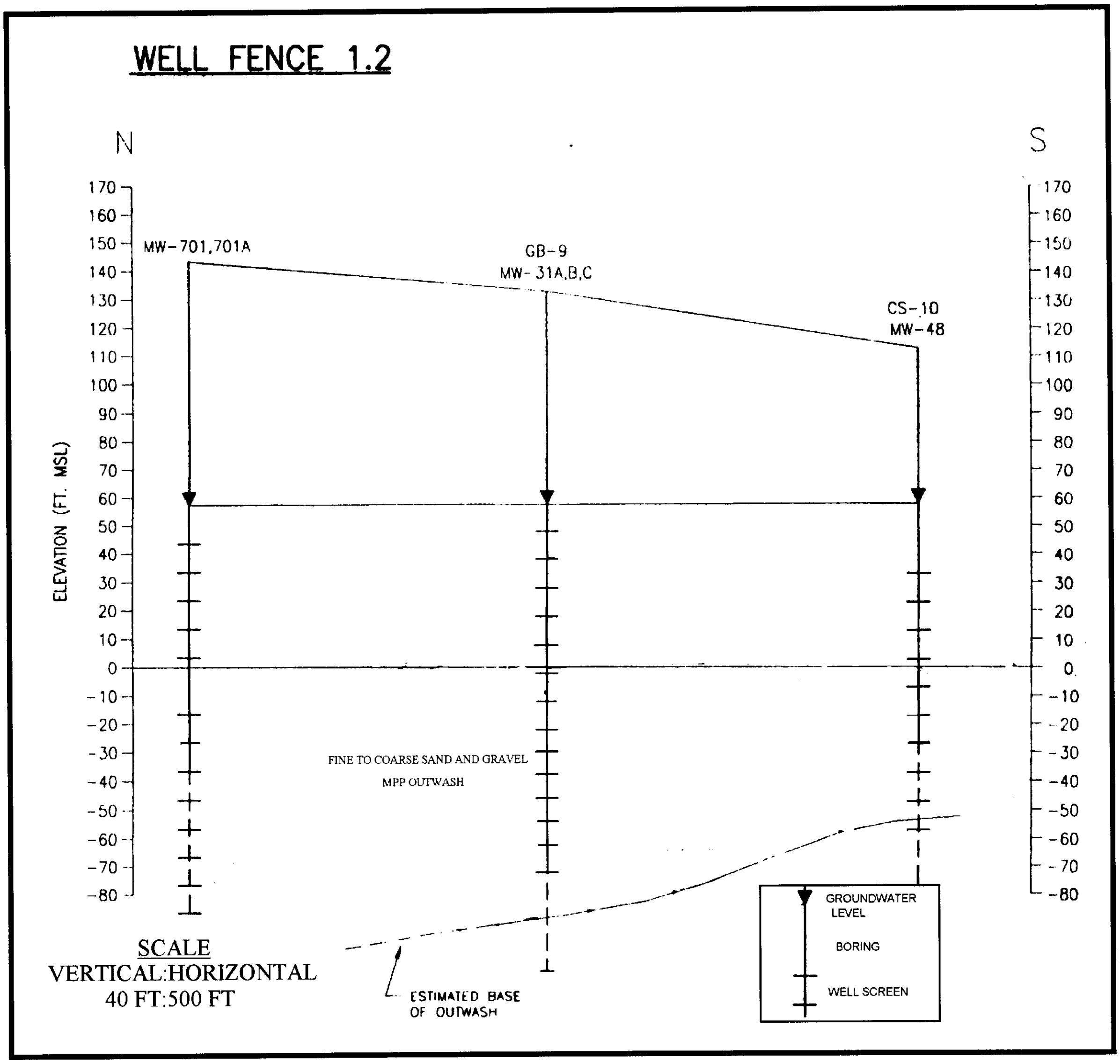


Figure 3-9, Well Fence 1.2 (CDM, 1996)

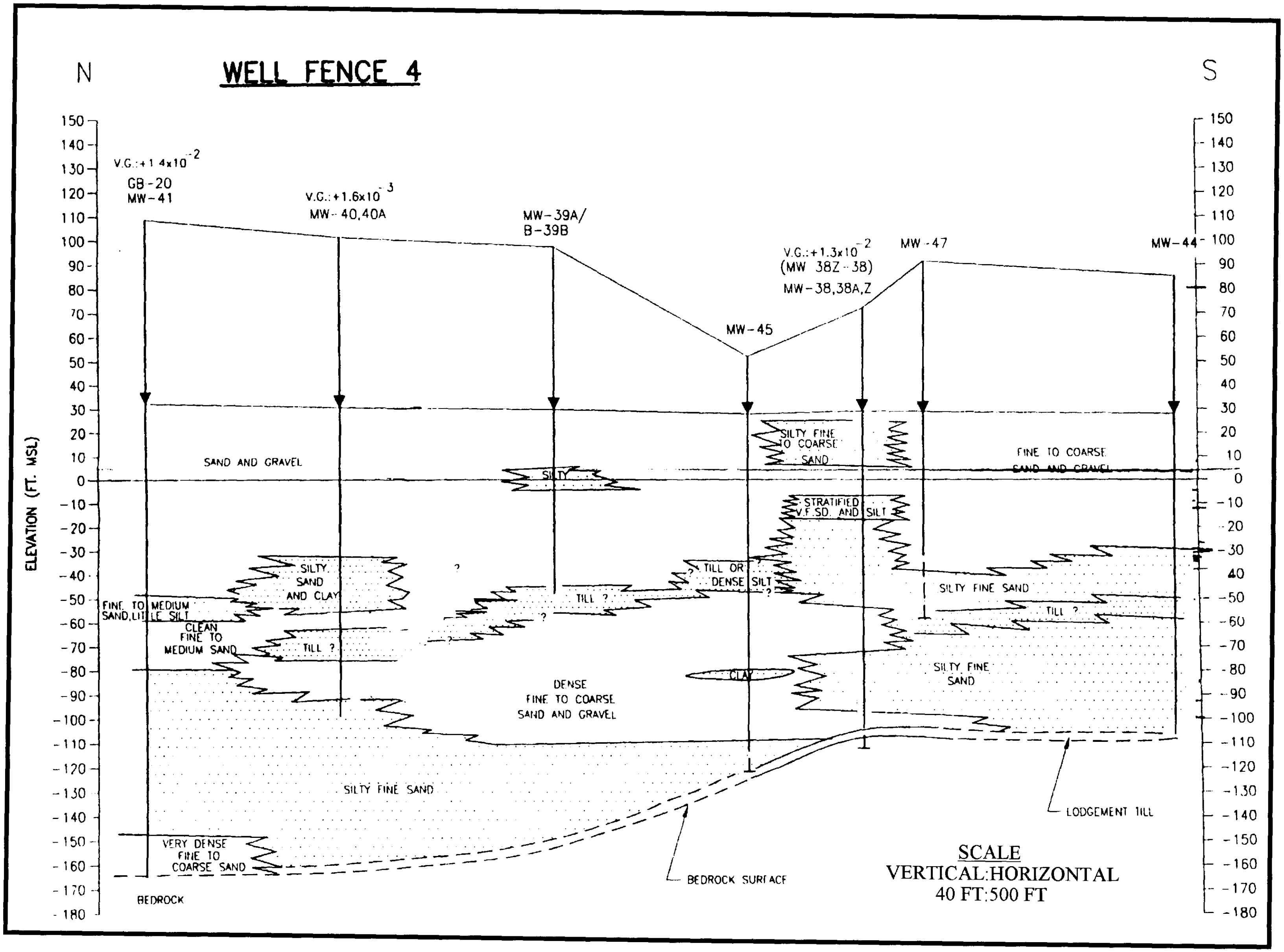


Figure 3-10, Well Fence 4 (CDM, 1996)

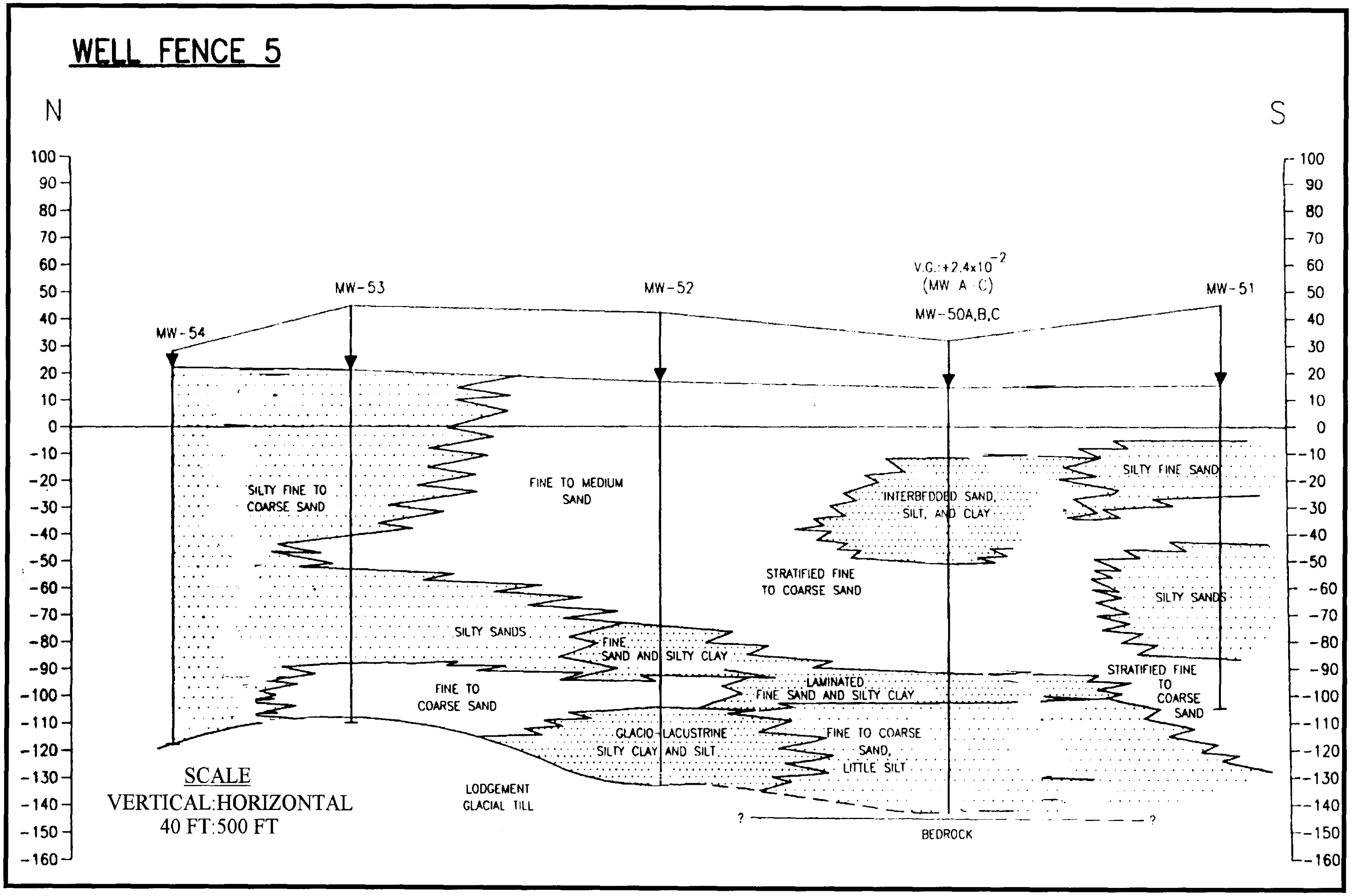


Figure 3-11, Well Fence 5 (CDM, 1996)

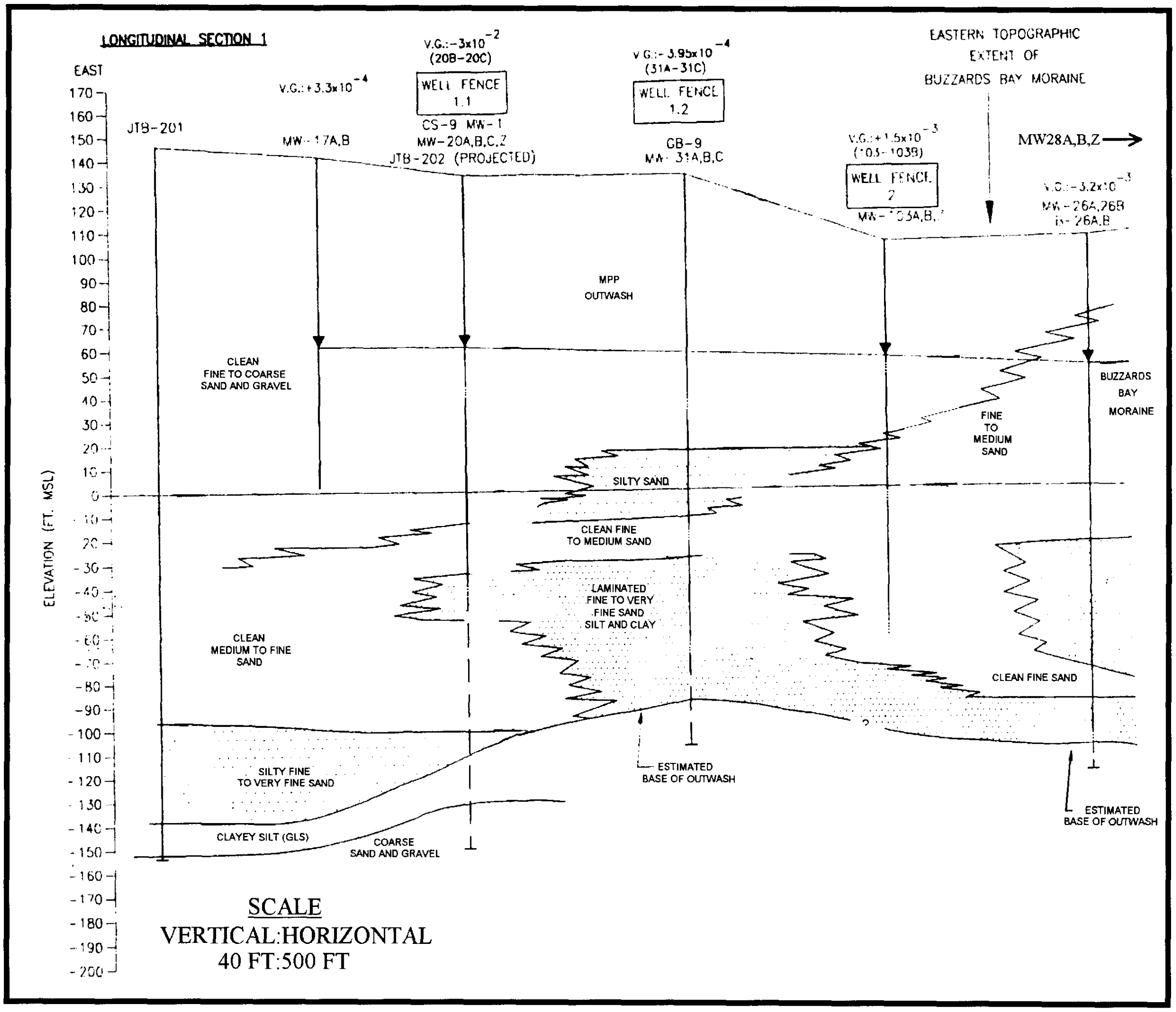


Figure 3-12, Longitudinal Section 1 (CDM, 1996)

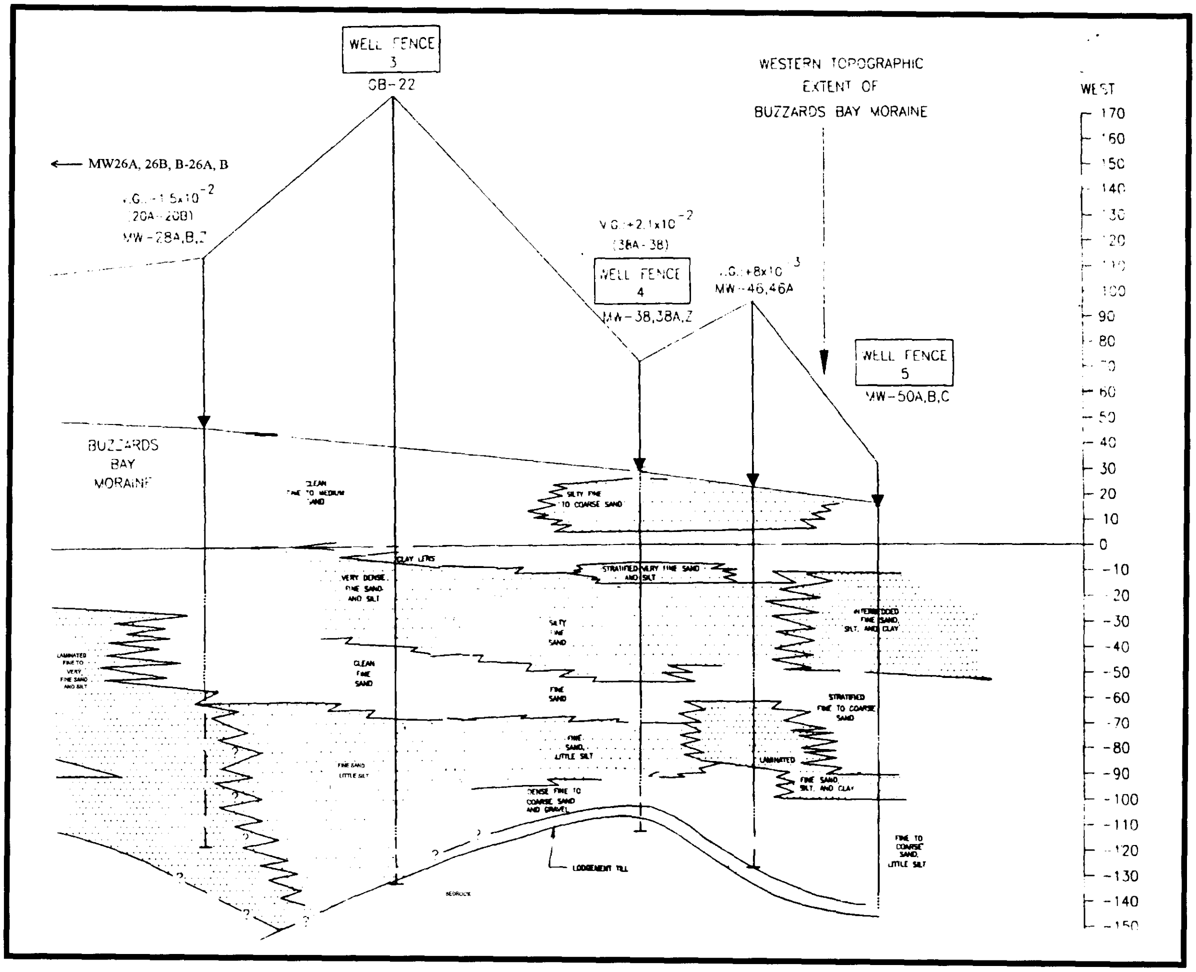


Figure 3-13, Longitudinal Section 1, continued (CDM, 1996)

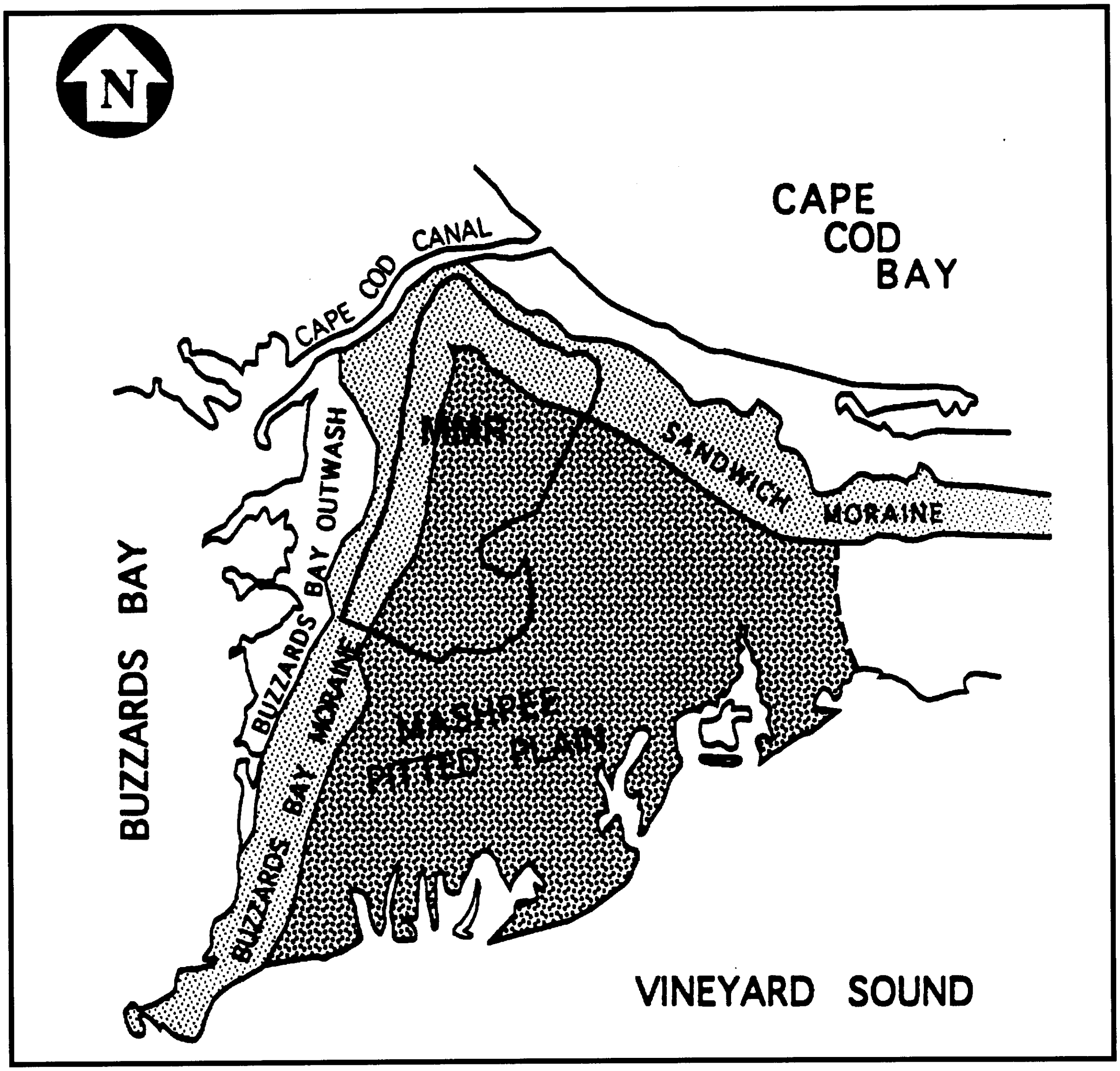


Figure 3-14, MMR Deposits (E.C. Jordan, 1989)

3.2.1.3 Hydrogeology

Western Cape Cod's groundwater system is an unconfined aquifer which is recharged by infiltration from precipitation. The water table resembles a mound. Groundwater flows radially outward from the top of the mound (Figure 3-15) with gradients ranging from 0.0013 to 0.0068 ft/ft along Longitudinal Section 1 in Figures 3-12 and 3-13 (CDM, 1996). Although vertical flow occurs in the aquifer, it is negligible and flow is predominantly horizontal. In the LF-1 area and to the west, the mean groundwater table elevation is approximately 65 feet below ground surface.

The hydraulic conductivity of the MPP outwash soils varies greatly throughout the formation, ranging from approximately 0.06 ft/day to approximately 306 ft/day (CDM, 1996). The hydraulic conductivity of the finer-grained GLS sediments underlying the outwash range from approximately 0.04 ft/day to approximately 0.11 ft/day (CDM, 1996). In the BBM, the hydraulic conductivity is generally lower than in the MPP in addition to generally decreasing with depth. Hydraulic conductivity in the BBM ranges from approximately 0.01 ft/day to approximately 240 ft/day. Most of the regional groundwater flow occurs in the upper, coarse sand and gravel layer of the MPP. Horizontal flow velocities range from 1 to 3.4 ft/day (CDM, 1996).

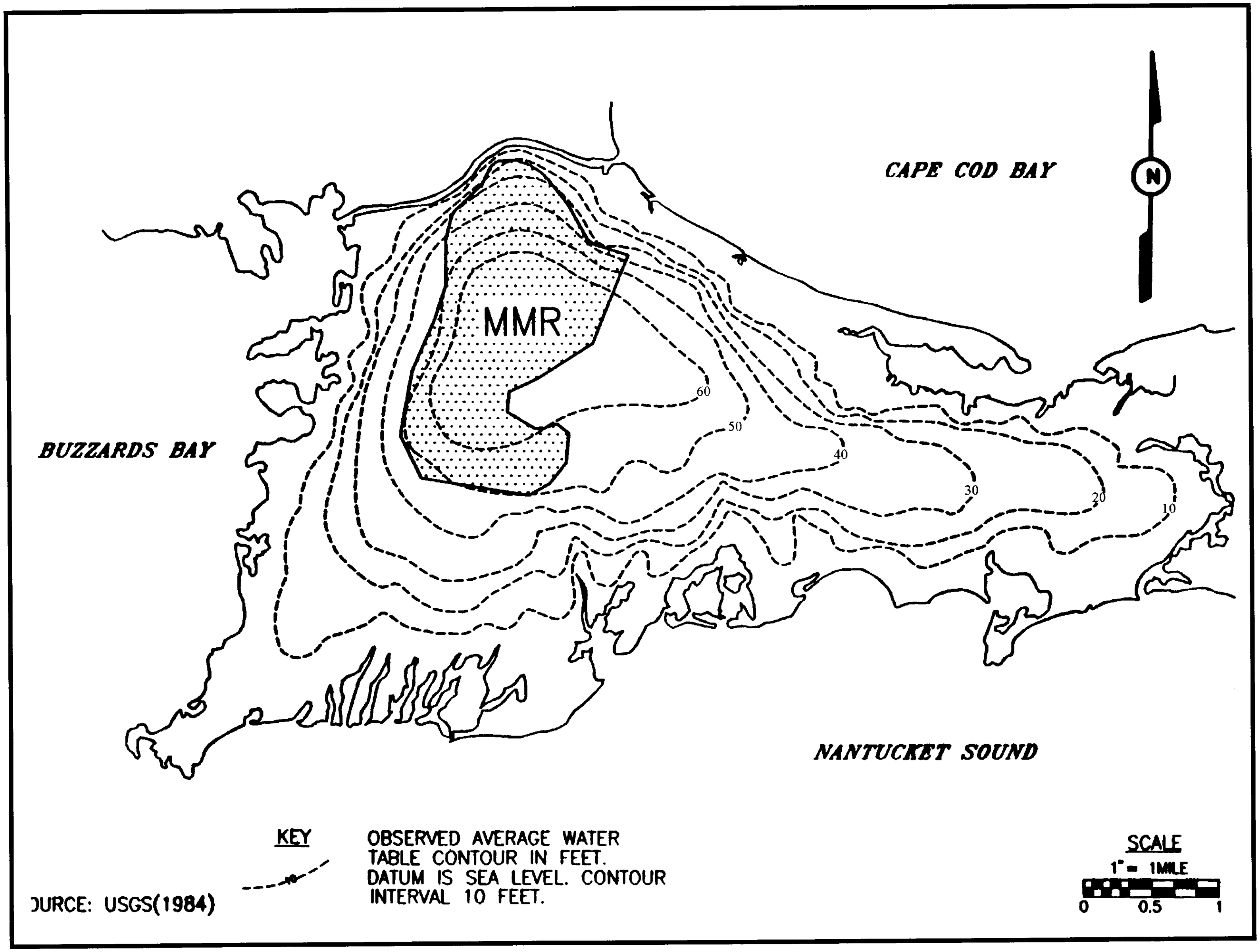


Figure 3-15, Water Table Map of Upper Cape Cod (CDM, 1996)

3.2.2 Selection of Well Materials

Materials required to construct an environmental horizontal well include a production liner (well screen), a transition filter (filter pack), and a submersible pump. The liner must be able to withstand both degradation (chemical and physical) by contaminants and applied stresses during installation. Possible liner materials include slotted polyvinyl chloride (PVC), slotted high density polyethylene (HDPE), steel composite screens with stainless-steel mesh inserts in a thermoplastic-based (HDPE) pipe, wire-wrapped screen with PVC and stainless pipe, several pre-packed screen types, and fiberglass. The durability of the well screen is important for long-term (usually thirty years or more) remediation systems. PVC is both lightweight and resistant to corrosion and is somewhat flexible. PVC can also be threaded, making installation easier. However, PVC is also subject to long-term creep effects, so it is not very durable. Steel is strong, but it is even less flexible than PVC. Like PVC, HDPE is lightweight and corrosion resistant, but also more durable and flexible, capable of bending up to 15 degrees. However, HDPE cannot be threaded; it must be heat-fused onsite. Fiberglass is also lightweight and corrosion resistant, but it is very brittle. The final decision of which material to use depends on hydrogeological conditions, remedial objectives, and economics. HDPE appears to be the best well material for the LF-1 site.

Additional factors to consider in the selection of well screen are slot size, screen length, and screen diameter. The size of the slots depends on the grain size of the filter pack. An alternative to slots is wire-mesh screen elements in HDPE, which can screen finer particles than slotted pipe. An additional advantage of these wire-mesh screen elements is that they promote development of a natural filter pack in well-graded sands and silts. This can eliminate the need for expensive gravel-packing technology. The length of the screen depends on hydrogeologic considerations, such as the required capture zone size. Well screen diameter must take into account both pump size (capacity) and open screen-area requirements (related to pumping/injection rates). In addition, the pressure drop along the length of the screen must be considered, as this can significantly reduce the well's intake from the far end of the screen because of the frictional energy losses required to produce this section. It has been observed that 500 feet of smooth, four-inch screen with a production of more than 100 gpm will cause head loss significant enough to prevent uniform intake flow along the well and reduce overall efficiency (Karlsson, 1993). These three parameters, slot size and filter material, screen length, and screen diameter, should be decided in consultation with the drilling contractor.

Filter packs around the well screen are necessary in order to prevent fine-grained soil from entering the well. Sand packs are commonly used and installed via tremie tube in the annular space around the well screen. However, filter packs can also be in the form of prepacked screens, which are easier to install and more efficient, but are not very flexible. Prepacked screens can also be removed for maintenance, unlike conventional sand packs. Other filter pack options include the use of geofabrics, which have the necessary flexibility but may not be as durable or efficient as sand packs. Considering the large turning radius, the length of the wells, and the design life of the system, prepacked screens may be the best option for the LF-1 site.

The choice of pump depends on predicted pumping/injection rates. Centrifugal, electrical submersible pumps are best for high volume remediation systems. Pneumatic pumps can provide continuous pumping below two gpm and are best for low volume systems (Karlsson, 1993).

3.2.3 Well Placement

As stated in Section 3.1.2.1, six biozones were considered for the bioremediation design using 14 vertical wells, half of which already exist. The locations of the biozones are shown on Figure 3-6. In order to implement that bioremediation scheme, seven additional vertical wells must be constructed. However, it was concluded that the design was not feasible due to the high injection rates required for the individual wells (Haghseta, 1997). The injection rates could be reduced by the use of additional vertical wells or the use of horizontal wells, either alone or in combination with existing vertical wells, to create the aerobic and anaerobic biozones. Well depths were not specified in the bioremediation scheme proposed by Haghseta (1997) because it was a two-dimensional conceptual design. The depths of either type of well should be based on the location of the plume, which reaches an average depth of approximately 150 feet below ground surface (CDM, 1995b).

3.3 Comparison with Vertical Wells

The advantages of horizontal wells over vertical wells was discussed in Section 3.1.1. In practice, the comparison between the two well types comes down to two criteria: performance and cost.

3.3.1 Performance

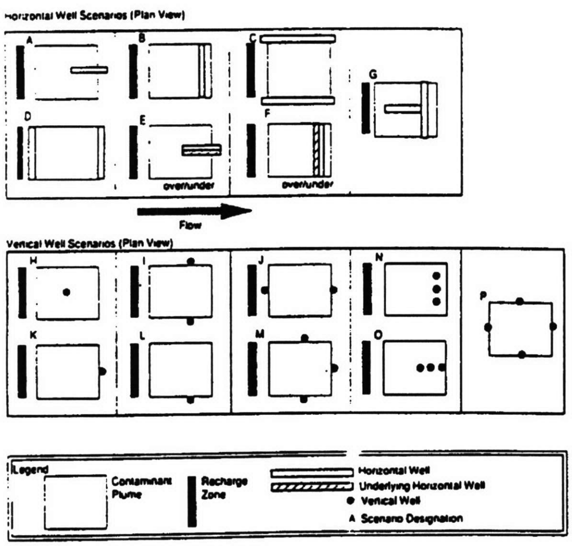
Horizontal well hydraulic performance is not as well known as that of vertical wells. Therefore, hypothetical and case study modeling of horizontal wells and vertical wells was performed by Arthur D. Little, Inc., in order to evaluate contaminant removal effectiveness using numerical models of groundwater flow and contaminant transport during pumping. The scope of the study included the assessment of the effects of hydrogeologic and plume variations and the relative contaminant capture effectiveness of vertical and horizontal wells for various well configurations in three different contamination schemes. According to Langseth (1990), the author of the paper, horizontal well performance can theoretically be modeled by a series of closely-spaced vertical wells with short screened intervals.

The three contamination scenarios for the hypothetical modeling were as follows: a thick existing contaminant plume with length to width to thickness ratio 9L:9W:9T, a thin existing contaminant plume with length to width to thickness ratio 9L:9W:1T, and a radial active leachate plume from a landfill. Various horizontal and vertical extraction well arrays were then selected and optimized with respect to well placement for each configuration. For the thick plume, the hypothetical study showed that although several horizontal and vertical well configurations perform comparably for contaminant capture, the fastest capture rate was obtained from a horizontal well scheme, orientation G (Figure 3-16). This orientation was comprised of two perpendicular wells forming a "T", with the stem of the "T" lying in the direction of flow and the bar of the "T" positioned at the downstream end of the stem. Horizontal wells in orientations G and B (Figure 3-16) provided the best performance for the thin plume. Orientation B consists of a single well positioned perpendicular to the direction of flow.

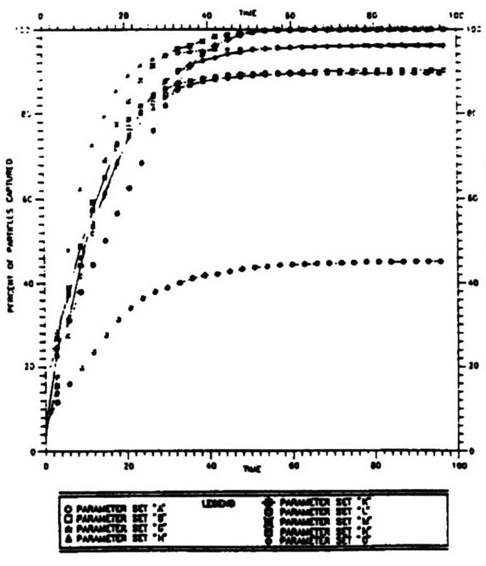
Figures 3-16 and 3-17 summarize the model parameter sets used for the hypothetical study, shows plan views of the well scenarios, and presents results of percentage of contaminants captured as a function of time in years for various well orientations for the thick plume, the thin plume, and a radial contaminant source. Table 3-3 presents the results of the performance of horizontal and vertical well configurations in the hypothetical study, measured by capture rate and total particle capture, as aquifer characteristics are varied (Langseth, 1990). In general, the horizontal wells performed better than the vertical wells.

Model Parameter Sets Used for the Hypothetical Model

Parameter Set	Delta X Spacing (meters)	Delta Y Spacing (meters)	Delta Z Spacing (meters)	Boundary Conditions	Simulation Type	Layer Type	Hydraulic Conductivity (meters/day)	Transverse Hydraulic Conductivity (meters/day)	Vertical Hydraulic Conductivity (meters/day)	Gradient	Total Recharge (M³ /day)	Pumping Rate per Cell (M³ /day)	Modification of Parameter Set 1
1	1	1	1	Constant head along rows 1 and 25, all other cells active	Steady state	Layer 1 unconfined; layers 2 through 25 fully convertible between confined and unconfined	8.64	8.64	8.64	0.005	9	1	None
2	•	•	•	•	•	•	•	•	•	•	18	1	Well location shifted slightly, two well scenario only
3	•	•	•	•	•	•	•	•	•	•	•	Well #1 at 0.9 Well #2 at 1.1	Wells pumping at different rates, two well scenario only
4	•	•	•	•	•	•	0.864	•	•	•	9	1	Change in hydraulic conductivity values
5	•	•	•	•	•	•	8.64	•	•	0.05	•	•	Change in gradient values
6	•	•	•	•	•	•	•	•	0.864	0.005	•	•	Change in conductance values
7	•	•	•	•	•	•	•	0.864	8.64	•	•	•	Reduction in transverse hydraulic conductivity anisotropy value
8	•	•	•	•	•	•	•	86.4	•	None	•	•	Increase in transverse hydraulic conductivity anisotropy value
9	•	•	•	•	•	•	•	8.64	•	•	•	•	Radial flow source inserted at grid center and recharge from wells eliminated

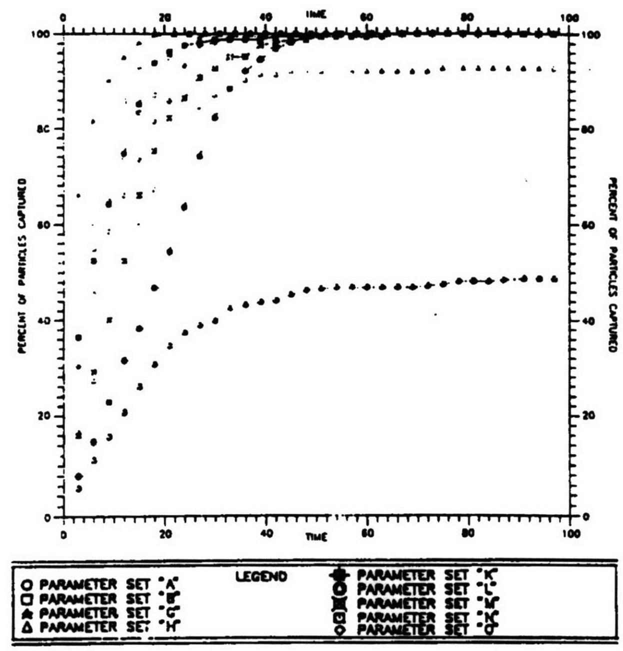


Horizontal Well Scenarios (Plan View)
Vertical Well Scenarios (Plan View)

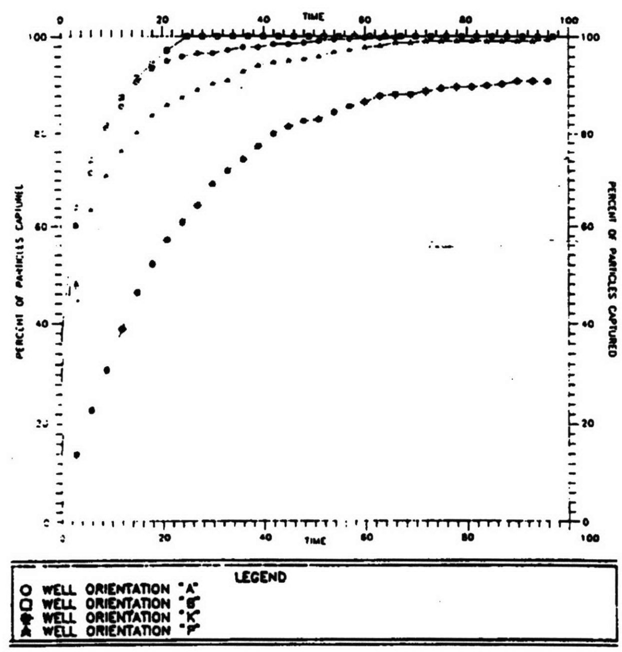


Contaminant Plume Ratio 9L:9W:9T
Percentage of Contaminants Captured vs. Time
Various Well Orientations;
Parameter Set 1

Figure 3-16, Hypothetical Model Parameters, Well Scenarios, and Capture (Langseth, 1990)



Contaminant Plume Ratio 9L:9W:1T
Percentage of Contaminants Captured vs. Time
Various Well Orientations;
Parameter Set 1



Plume 3
Percentage of Contaminants Captured vs. Time
with a Radial Recharge and Contaminant Source
Various Well Orientations;
Parameter Set 9

Figure 3-17, Hypothetical Model Capture, continued (Langseth, 1990)

Table 3-3, Performance of Well Orientations by Varying Aquifer Characteristics

Aquifer Characteristic	Fastest Capture Rate		Highest Total Capture	
	Thin Plume	Thick Plume	Thin Plume	Thick Plume
Base case parameter set	horizontal	horizontal	horizontal	vertical
Reduction in horizontal K	horizontal	horizontal	horizontal	horizontal
Increase in groundwater gradient	horizontal	horizontal	horizontal	horizontal
Reduction in vertical K	horizontal	vertical	horizontal	vertical
Reduction in transverse K	horizontal	horizontal	horizontal	horizontal
Increase in transverse K	horizontal	tie	horizontal	tie
With vertical recharge	horizontal	horizontal	horizontal	horizontal
With a horizontal recharge doublet	horizontal	horizontal	horizontal	horizontal
With a vertical recharge doublet	horizontal	horizontal	horizontal	horizontal
With no recharge	horizontal	horizontal	horizontal	horizontal

Modified from Langseth (1990).

Unlike the hypothetical study, the case study evaluated the performance of only two well arrays, a set of eight vertical wells and a set of four horizontal wells, in cleaning up VOCs at a site. The design pumping rate used for each configuration was chosen based on a maximum allowable drawdown of 10 feet for individual wells. This gave a pumping rate of 709 gpm for the vertical array and 662 gpm for the horizontal array (Langseth, 1990). The results show that the performance of the horizontal wells was superior to that of the vertical wells in all of the areas evaluated (Table 3-4). Specifically, after five, ten, and twenty years of pumping, horizontal wells removed 77%, 84%, and 85% of contamination, respectively, compared to 59%, 75%, and 76%, respectively, for vertical wells (Langseth, 1990). In addition, the percentage of contamination which migrated offsite after 20 years of pumping was much lower for the horizontal well array—13.4% migration, compared to 22.3% migration for the vertical well array (Langseth, 1990). Figure 3-18 summarizes the contaminant capture rates for each configuration.

Table 3-4, Case Study Contaminant Cleanup Over Time

Measure of Performance	After 5 Years of Pumping		After 10 Years of Pumping		After 20 Years of Pumping	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Total volume of contaminated water in the aquifer (m^3)	354,000	492,000	210,000	260,000	102,000	101,000
Average concentration of the contaminated grid cells (ppb)	3,628	6,380	1,901	2,229	1,509	1,421
Percentage of contamination removed by wells	77	59	84	75	85	76
Percentage of contamination that traveled offsite	12	16	12	20	13.4	22.3
Percentage of contamination remaining in the aquifer onsite	11	25	4	5	1.6	1.7

Modified from Langseth (1990).

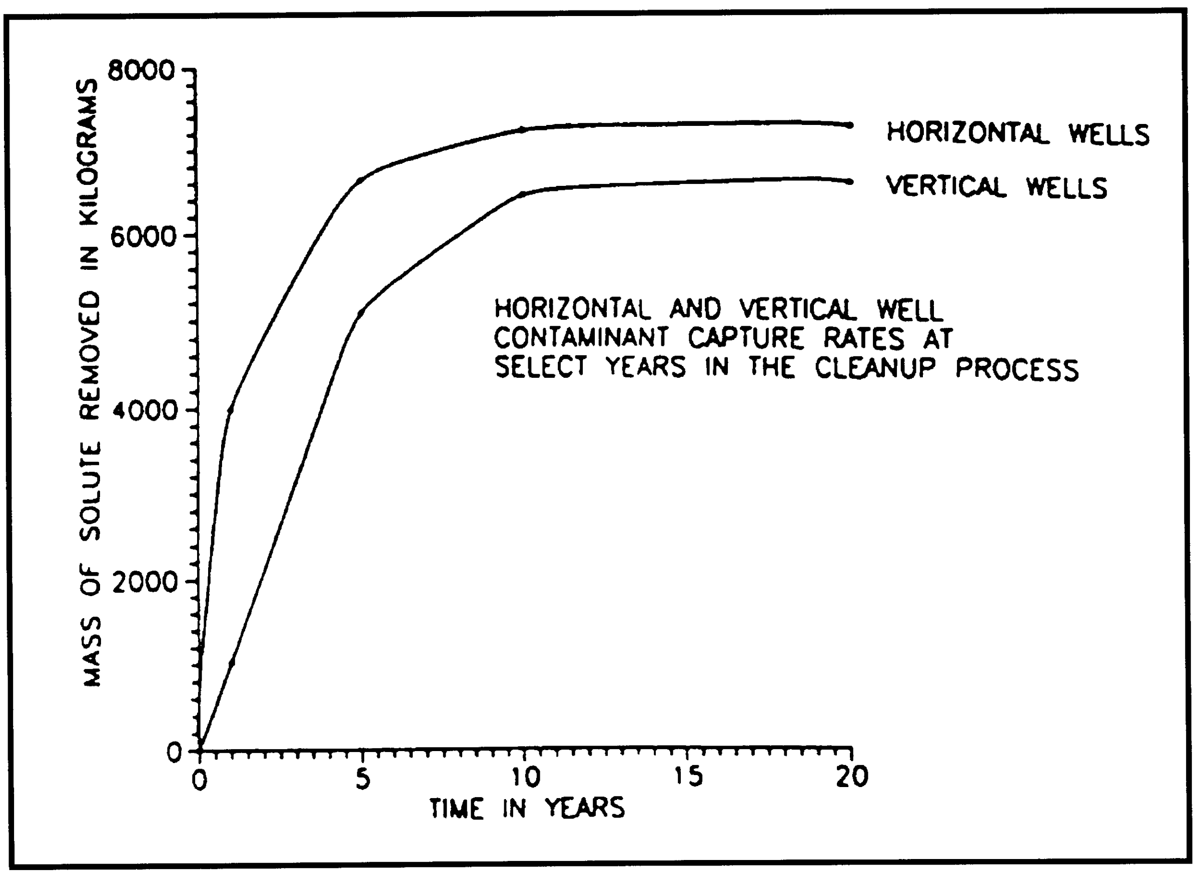


Figure 3-18, Case Study Contaminant Capture Rates (Langseth, 1990)

It is apparent from the hydraulic performance study that horizontal wells can be more efficient than vertical wells under certain conditions, configurations, and applications. Russell (1996) estimates that "for a given formation, the increase in efficiency is directly proportional to the increase in well length in the formation. For example, a 20-foot vertical well is only one-sixth as efficient as a 120-foot horizontal well for a given lithology." Assuming a maximum effective screened length of 2,000 feet for a horizontal well and 150 feet for a vertical well at the LF-1 site, a horizontal well can be up to 13 times more efficient than a vertical well by Russell's estimate.

3.3.2 Economic

The total cost of well installation, whether horizontal or vertical, includes both installation, and operation and maintenance. Installation costs include permitting, drilling, materials (well screen, filter pack, pumps), well vault and surface piping, well development, laboratory analyses, and pumping tests. Operation and maintenance costs include utilities, spare parts and repairs, sampling and testing, and general maintenance. The results of three studies are discussed below.

3.3.2.1 Comparison by Langseth (1990)

Langseth (1990) compares the cost of the two arrays used in the hydraulic performance case study model described in Section 3.3.1. He states that the difference in operation and maintenance costs and in recharge system costs for the two systems are negligible and thus does not consider them in his evaluation. Therefore, his comparison evaluates the operation and maintenance costs associated with three different treatment technologies (air stripping, air stripping with carbon adsorption, and carbon adsorption) for a given site and obtains the differences in net present value of operation and maintenance for varying treatment periods. The purpose of this approach was to determine whether the greater capture rate of the horizontal well system could shorten the cleanup time enough to justify its much larger installation cost. Langseth's evaluation shows that it does, especially for the air stripper with carbon adsorption and the carbon adsorption treatment systems (Table 3-5). For example, the cost of running a vertical well-carbon adsorption system for ten years is $4 million, versus $2.8 million for a horizontal well-carbon adsorption system operating for only five years to the same cleanup level. This gives a savings of $1.2 million dollars, or 30%.

Table 3-5, Horizontal vs. Vertical Well Costs I

Case	Air Stripping		Air Strip.-Carbon Adsorp.		Carbon Adsorption	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
Capital Costs[1]	$475,000	$260,000	$740,000	$525,000	$1,400,000	$1,185,000
Annual O&M[2]	$47,000	$47,000	$171,500	$171,500	$320,000	$320,000
Years of Operation[3]	5	10	5	10	5	10
Cum. O&M Cash Flow[4]	$273,000	$562,000	$960,000	$1,968,000	$1,422,000	$2,829,000
NPV of O&M[5]	$239,000	$378,000	$881,000	$1,395,000	$1,644,000	$2,603,000
Total Cumulative Cost[6]	$748,000	$822,000	$1,700,000	$2,493,000	$2,822,000	$4,014,000
Total NPV[7]	$714,000	$638,000	$1,621,000	$1,920,000	$3,044,000	$3,788,000
Cost Differential	Cumulative	$74,000	Cumulative	$793,000	Cumulative	$1,192,000
(Horizontal vs. Vertical)	NPV	($76,000)	NPV	$299,000	NPV	$744,000

Modified from Langseth (1990).

Notes:
1) Capital costs include the costs of installation the well array and the treatment system.
2) Annual O&M costs of the treatment system.
3) Years to achieve cleanup for the carbon adsorption system.
4) Cumulative cash flow of O&M is based on 5% inflation rate.
5) Net present value of O&M is based on 12% hurdle rate.
6) Total cumulative cost is capital costs plus cumulative cash flow of O&M.
7) Total net present value is capital costs plus net present value of O&M.

3.3.2.2 Comparison by Karlsson (1993)

Karlsson (1993) compares the cost of one horizontal well with the cost of (1) using five vertical wells in a sandy aquifer for the purpose of preventing off-site migration of contaminant and (2) using ten vertical wells in a silty clay aquifer for the purpose of plume recovery (Table 3-6). Karlsson's evaluation does not include the cost of surface treatment or take remediation times into account. He considers only installation (drilling, parts and equipment, and testing) and annual operating (sampling, testing, repairs, and parts and equipment) costs. He calculates total project costs for a ten-year period of \$262,000, \$673,000, and \$1,346,000 for the horizontal well, the five vertical wells, and the ten vertical wells, respectively, over a ten-year project period (Table 3-6).

Table 3-6, Horizontal vs. Vertical Well Costs II

Number/Type of Wells	1 Horizontal	5 Vertical	10 Vertical
Soils	Either	Sand	Silty Clay
Screen Length (each)	400 ft	10 ft	10 ft
Installation Costs			
Total Drilling Cost	$80,000	$35,000	$70,000
Recovery Pumps	5,000	15,000	30,000
Surface Piping to Treatment	3,000	30,000	60,000
Surface-pipe Trenching	0	12,000	24,000
Well Development	0	4,000	8,000
Chemical Analyses	600	3,000	6,000
Pump Test (conductivity)	3,400	14,000	28,000
Total Installation Costs	**$92,000**	**$113,000**	**$226,000**
Annual Operating Costs			
Static Water Elevations	$2,000	$10,000	$20,000
Reconditioning & Sampling	6,000	16,000	32,000
Quarterly Analyses	2,400	12,000	24,000
Pump Spare Parts & Repairs	1,000	3,000	6,000
Pump Tests	2,000	6,000	12,000
Electricity	3,600	9,000	18,000
Total Annual Operating Costs	**$17,000**	**$56,000**	**$112,000**
Total Project Cost (10 years)	**$262,000**	**$673,000**	**$1,346,000**

Modified from Karlsson (1993).

Notes: Does not include water treatment costs.
The five vertical well system represents a purge line to prevent off-site migration of contaminant.
The 10 vertical well system represents a plume recovery system.

3.3.2.3 Comparison by May (1994)

May (1994) compares the cost of one horizontal well with five, ten, and twenty vertical wells in sandy, silty clay, and clay aquifers, respectively, with no particular application specified. He includes well abandonment costs in his evaluation. May determined total project costs of $108,500, $212,500, $425,000, and $850,000 for the horizontal well and the five, ten, and twenty vertical wells, respectively, over a five-year period (Table 3-7).

Table 3-7, Horizontal vs. Vertical Well Costs III

Number/Type of Wells	1 Horizontal	5 Vertical	10 Vertical	20 Vertical
Horizontal/Soils	500 ft	sandy	silty clay	clay
Drilling Costs				
Permitting	$500	$2,500	$5,000	10,000
Drilling, incl. Mob.	70,000	50,000	100,000	200,000
Pump Installation	3,000	15,000	30,000	60,000
Vault & Surface Piping	3,500	17,500	35,000	70,000
Project Supervision	2,500	2,500	5,000	10,000
Total Drilling Costs	**$79,500**	**$87,500**	**$175,000**	**$350,000**
Annual Operation Costs				
Utilities	$1,200	6,000	$12,000	24,000
Pump Repairs	600	3,000	6,000	12,000
Sampling & Testing	2,400	12,000	24,000	48,000
Capital Maintenance	600	3,000	6,000	12,000
Total Annual Operation Costs	**$4,800**	**$24,000**	**$48,000**	**$96,000**
First Year Costs	**$84,300**	**$111,500**	**$223,000**	**$446,000**
Plug & Abandon	5,000	5,000	10,000	20,000
Five Year Costs	**$108,500**	**$212,500**	**$425,000**	**$850,000**

Modified from May (1994).

Notes: The vertical depth of all wells is 50 feet.

Chart compares the cost of a typical horizontal well with five, ten, and twenty vertical wells drilled to the same vertical depth in three different soil conditions.

These three studies show that although drilling costs for a horizontal well are much higher than that of individual vertical wells, the overall costs, including operation and maintenance, of horizontal well systems are generally much more economical than vertical well systems.

4. SUMMARY AND CONCLUSIONS

4.1 Overview of Horizontal vs. Vertical Wells for Environmental Remediation

Horizontal wells can be used for several applications, including the following: soil vapor extraction; use in traditional pump and treat remediation systems; air sparging; injection of bioenhancers for bioremediation; NAPL investigation and recovery; vadose zone monitoring; leachate collection; and hydraulic gradient control (i.e., pumping).

Horizontal directional drilling is a relatively new technique. However, over 200 well installations have been performed for remediation to date and the technology is constantly improving.

Horizontal wells are, in many cases, more efficient and hence more cost effective than vertical wells, as shown in Section 3.3.2. Other advantages over vertical wells include the following:

- Because the screened length of the well does not lie directly under the entry point, horizontal wells can be used in places where vertical wells cannot, because of access restrictions or because of the necessity of interrupting operations at the site.

- Horizontal wells can be aligned with the principal plume axis for more efficient remediation as the result of a large, elongated zone of influence, a horizontally continuous capture zone, high specific capacity, and a long screen with low screen-entrance velocities. Hence, one horizontal well can replace several vertical wells.

Many types of horizontal directional drilling systems are available; however, the most commonly used in the environmental industry are medium rigs which utilize rotary drilling with a mud motor; either a walkover radio-frequency guidance system for shallow bores or a downhole electromagnetic telemetry guidance system for deeper bores; and a drilling fluid which does not spread existing contamination, contribute new contamination, or damage the formation's permeability while having the proper balance of viscosity and gel strength to efficiently remove drill cuttings. Medium rigs can drill 12-inch diameter horizontal boreholes up to 2,000 feet in length.

The selection of well materials, such as well screen/liner, filter pack, and pumps are very important. Well screen and filter pack are installed by pushing or pulling through the borehole. These materials are easier to install in continuous wells than in blind wells. The two types of wells are illustrated on Figure 3-1. The well screen must be durable, corrosion resistant, and somewhat flexible. Its length, diameter, and slot size will depend on the site conditions (both stratigraphic and hydrogeologic) and the design goals of the project.

4.2 Use of Horizontal Wells for Bioremediation of LF-1

The use of horizontal wells was considered for bioremediation, DNAPL investigation, and post-closure management in this thesis. For bioremediation at the LF-1 site, horizontal wells can be used with greater efficiency than vertical wells to create aerobic and anaerobic biozones for the degradation of PCE and TCE and to inject nutrients.

Because horizontal wells can be oriented in any direction in the subsurface, they can be very effective for DNAPL investigation, and remediation of DNAPLs. And because horizontal wells can be installed beneath surface obstructions, they can be used for landfill post-closure activities such as vadose-zone monitoring or retroactive leachate control.

The bioremediation scheme as proposed by Haghseta (1997) was concluded not to be feasible due to the high injection rates (613 gpm to 2,810 gpm for vertical wells; it will be less for horizontal wells) necessary for the plan. However, using horizontal wells for bioremediation at the LF-1 site can enhance the proposed design and is technically feasible, but further study is needed to determine if it is economically feasible. The following conclusions and recommendations are made.

- If horizontal wells are drilled at the LF-1 site, a medium or large rig which utilizes rotary drilling with a mud motor; a downhole electromagnetic telemetry guidance system; and an appropriate drilling fluid should be used.

- Because of its physical properties, HDPE appears to be the best well screen material for this project. Due to the low percentage of fines in the natural soils, a standard slot size of 0.010 inch will probably be sufficient. A pre-packed screen, because of the greater ease of installation, should be considered for use.

- Again, because of the high injection rates, relatively large diameter (up to eight inches) wells should be installed. The large diameter wells will also have lower head loss. The screen length is limited by the maximum drilling distance of the rig; this will be approximately 2,000 feet for a medium rig. If a large rig is used, the wells can be longer than 2,000 feet. However, a cost analysis would need to be performed to determine if the higher cost is offset by the benefits of utilizing the large rig.

These recommendations are fairly general. A more detailed design is beyond the scope of this thesis, which is intended only to give an overview of the requirements of the LF-1 site and a discussion and comparison of the technology available, its performance, and its cost. Better theoretical models are needed to predict the performance of horizontal wells because knowledge in this area is limited at the present time. In addition, given the range of requirements and variables for which to account, the input of experienced drilling contractors is essential for making final decisions in the field.

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